

TITLE OF THE INVENTION

NOVEL MONOTHIOL MUCOLYTIC AGENTS

CONTINUING APPLICATION INFORMATION

The present application claims benefit to U.S. Provisional Application Serial No. 62/109,999, filed on January 30, 2015, and incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to novel monothiol mucolytic agents. The present invention also includes a variety of methods of treatment using these inventive mucolytic agents.

Description of the Background

The mucosal surfaces at the interface between the environment and the body have evolved a number of “innate defense”, *i.e.*, protective mechanisms. The mucus transport system is the fundamental defense of the airways against inhaled particulates/infectious agents. Inhaled particles are trapped in the mucus layer and subsequently propelled out of the lungs via mucus clearance. The mucus transport system requires that mucus be well hydrated to facilitate ciliary clearance. In the absence of sufficient mucus hydration, the mucus becomes excessively viscous and adherent, which can lead to airway mucus accumulation and infection.

Typically, the quantity of the liquid layer on a mucosal surface reflects the balance between epithelial liquid secretion, often reflecting anion (Cl^- and/or HCO_3^-) secretion coupled with water (and a cation counter-ion), and epithelial liquid absorption, often reflecting Na^+ absorption, coupled with water and counter anion (Cl^- and/or HCO_3^-). Many diseases of mucosal surfaces are caused by too little protective liquid on those mucosal surfaces created by an imbalance between secretion (too little) and absorption (relatively too much). The defective salt transport processes that characterize these mucosal dysfunctions reside in the epithelial layer of the mucosal surface.

Abnormalities in the mucus transport system characterize a complex of mucobstructive airway diseases that include cystic fibrosis (CF) and chronic bronchitis (CB). Normal mucus clearance requires 1) adequate hydration of the airway surface and 2) an absence of strong adhesive and cohesive interactions between mucus and cell surface. Hydration is defined by the concentrations of mucins in the periciliary and mucus layers. Ion transport properties regulate the amount of salt and water (i.e. the solvent) and goblet cells and glands control the quantity of mucins on the airway surface. Subjects with mucobstructive diseases including cystic fibrosis (CF), chronic bronchitis associated with cigarette smoke exposure, *i.e.*, COPD, and asthma exhibit increases in mucus concentration as quantified by % solids (see Figure 1), as a result of reduced airway hydration and mucin hypersecretion, consequent to goblet cell and glandular hyperplasia. Both as a function of disease severity, and in acute exacerbations, raised mucin concentrations produce adherent mucus that sticks to epithelial cells, impairs clearance, triggering inflammatory responses and airway wall injury, and serves as a growth medium for pathogenic microorganisms. Clearly, enhancing the clearance of such thickened/adhered mucus from the airways is likely to benefit patients with mucus-obstructive diseases.

Chronic bronchitis (CB), including the most common lethal genetic form of chronic bronchitis, cystic fibrosis (CF), are diseases that reflect the body's failure to clear mucus normally from the lungs, which ultimately produces chronic airways infection. In the normal lung, the primary defense against chronic intrapulmonary airways infection (chronic bronchitis) is mediated by the continuous clearance of mucus from bronchial airway surfaces. This function in health effectively removes from the lung potentially noxious toxins and pathogens. Recent data indicate that the initiating problem, *i.e.*, the "basic defect," in both CB and CF is the failure to clear mucus from airway surfaces. The failure to clear mucus reflects an imbalance between the amount of liquid and mucin on airway surfaces. This "airway surface liquid" (ASL) is primarily composed of salt and water in proportions similar to plasma (*i.e.*, isotonic). Mucin macromolecules organize into a well-defined "mucus layer" which normally traps inhaled bacteria and is transported out of the lung via the actions of cilia which beat in a watery, low viscosity solution termed the "periciliary liquid" (PCL). In the disease state, there is an imbalance in the quantities of mucus and ASL on airway surfaces. This results in a relative reduction in ASL which leads to mucus concentration, reduction in the lubricant activity of the PCL, and a failure to clear mucus via ciliary activity to the mouth. The reduction in mechanical clearance of mucus from the lung leads to chronic bacterial colonization of mucus adherent to airway surfaces. It is the chronic retention of

bacteria, the failure of local antimicrobial substances to kill mucus-entrapped bacteria on a chronic basis, and the consequent chronic inflammatory responses of the body to this type of surface infection, that lead to the syndromes of CB and CF.

The current afflicted population in the U.S. is 12,000,000 patients with the acquired (primarily from cigarette smoke exposure) form of chronic bronchitis and approximately 30,000 patients with the genetic form, cystic fibrosis. Approximately equal numbers of both populations are present in Europe. In Asia, there is little CF but the incidence of CB is high and, like the rest of the world, is increasing.

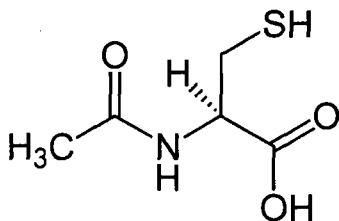
There is currently a large, unmet medical need for products that specifically treat CB and CF at the level of the basic defect that cause these diseases. The current therapies for chronic bronchitis and cystic fibrosis focus on treating the symptoms and/or the late effects of these diseases. Thus, for chronic bronchitis, β -agonists, inhaled steroids, anti-cholinergic agents, and oral theophyllines and phosphodiesterase inhibitors are all in development. However, none of these drugs treat effectively the fundamental problem of the failure to clear mucus from the lung. Similarly, in cystic fibrosis, the same spectrum of pharmacologic agents is used. These strategies have been complemented by more recent strategies designed to clear the CF lung of the DNA ("Pulmozyme"; Genentech) that has been deposited in the lung by neutrophils that have futilely attempted to kill the bacteria that grow in adherent mucus masses and through the use of inhaled antibiotics ("TOBI") designed to augment the lungs' own killing mechanisms to rid the adherent mucus plaques of bacteria. A general principle of the body is that if the initiating lesion is not treated, in this case mucus retention/obstruction, bacterial infections became chronic and increasingly refractory to antimicrobial therapy. Thus, a major unmet therapeutic need for both CB and CF lung diseases is an effective means of mobilizing airway mucus and promoting its clearance, with bacteria, from the lung.

Other mucosal surfaces in and on the body exhibit subtle differences in the normal physiology of the protective surface liquids on their surfaces but the pathophysiology of disease reflects a common theme, i.e., too little protective surface liquid and impaired mucus clearance. For example, in xerostomia (dry mouth) the oral cavity is depleted of liquid due to a failure of the parotid sublingual and submandibular glands to secrete liquid. Similarly, keratoconjunctivitis sicca (dry eye) is caused insufficient tear volume resulting from the failure of lacrimal glands to secrete liquid or excessive evaporative fluid loss. In rhinosinusitis, there is an imbalance, as in CB, between mucin secretion, relative airway surface liquid depletion, and mucus stasis. Finally, in the gastrointestinal tract, failure to

secrete Cl⁻ (and liquid) in the proximal small intestine, combined with increased Na⁺ (and liquid) absorption in the terminal ileum leads to the distal intestinal obstruction syndrome (DIOS). In older patients excessive Na⁺ (and volume) absorption in the descending colon produces constipation and diverticulitis.

The high prevalence of both acute bronchitis and chronic bronchitis indicates that this disease syndrome is a major health problem in the U.S. Despite significant advancements in the etiology of mucus obstructive diseases, pharmacotherapy of both CF and COPD have been characterized by an aging array of therapies, typically including inhaled steroids and bronchodilators for maintenance, and antibiotics and high-dose steroids for exacerbations. Clearly, what are needed are drugs that are more effective at restoring the clearance of mucus from the lungs of patients with CB/CF. The value of these new therapies will be reflected in improvements in the quality and duration of life for both the CF and the CB populations.

One approach to increase mucus clearance is to enhance the transportability of mucins via the disruption of the polymeric mucus structure. Mucin proteins are organized into high molecular weight polymers via the formation of covalent (disulfide) and non-covalent bonds. Disruption of the covalent bonds with reducing agents is a well-established method to reduce the viscoelastic properties of mucus *in vitro* and is predicted to minimize mucus adhesiveness and improve clearance *in vivo*. Reducing agents are well known to decrease mucus viscosity *in vitro* and commonly used as an aid to processing sputum samples (Hirsch, S.R., Zastrow, J.E., and Kory, R.C. Sputum liquefying agents: a comparative *in vitro* evaluation. *J.Lab.Clin.Med.* 1969. 74:346-353). Examples of reducing agents include sulfide containing molecules capable of reducing protein di-sulfide bonds including, but not limited to, N-acetyl cysteine, N-acetylcystein, carbocysteine, cysteamine, glutathione, and thioredoxin containing



proteins.

NAC

N-acetyl cysteine (NAC) is approved for use in conjunction with chest physiotherapy to loosen viscid or thickened airway mucus. Clinical studies evaluating the effects of oral or inhaled NAC in CF and COPD have reported improvements in the rheologic properties of mucus and trends toward improvements in lung function and decreases in pulmonary exacerbations (Duijvestijn YCM and Brand PLP.; Systematic review of N-acetylcysteine in

cystic fibrosis. *Acta Paediatr* 88: 38-41. 1999). However, the preponderance of clinical data suggests that NAC is at best a marginally effective therapeutic agent for treating airway mucus obstruction when administered orally or as an inhalation aerosol. A recent Cochrane review of the existing clinical literature on the use of NAC found no evidence to support the efficacy of NAC for CF (Nash EF, Stephenson A, Ratjen F, Tullis E.; Nebulized and oral thiol derivatives for pulmonary disease in cystic fibrosis. *Cochrane Database Syst Rev*. 2009; 21(1):CD007168.).

NAC, as a topical pulmonary therapeutic agent, is not optimal for the reduction of mucin disulfide bonds. Specifically, NAC does not possess the basic properties of an effective pulmonary drug as NAC (1) is a relatively inefficient reducing agent the airway surface environment (e.g. CF pH 6.5 – 7.2); and (2) is rapidly metabolized and cleared from the airway surface (Jayaraman S, Song Y, Vetrivel L, Shankar L, Verkman AS. Noninvasive in vivo fluorescence measurement of airway-surface liquid depth, salt concentration, and pH. *J Clin Invest*. 2001;107(3):317-24). For example, in the pH environment of the airway surface (measured in the range of pH 6.0 to 7.2 in CF and COPD airways), NAC exists only partially in its reactive state as a negatively charge thiolate (Jayaraman S, Song Y, Vetrivel L, Shankar L, Verkman AS. Noninvasive in vivo fluorescence measurement of airway-surface liquid depth, salt concentration, and pH. *J Clin Invest*. 2001;107(3):317-24) (Figure 3). Furthermore, in animal studies, ¹⁴C-labeled NAC, administered by inhalation, exhibits rapid elimination from the lungs with a half-life of approximately 20 minutes (unpublished observation). The relatively low reducing activity at of NAC physiologic airway pH and the short half-life of NAC on the lung surface provide an explanation for the lack of strong clinical evidence for effective mucus reduction in mucus obstructive diseases.

Additionally, NAC is most commonly administered as a concentrated inhalation solution (Mucomyst® is a 20% or 1.27M solution). However, the administration of concentrated NAC solutions impact the tolerability of NAC as it exaggerates (1) the unpleasant sulfur taste/odor; and (2) pulmonary side effects including irritation and bronchoconstriction which can require co-administration of rescue medications such as bronchodilators. Although Mucomyst was approved by the FDA in 1963, no other reducing agents administered as an inhalation aerosol are currently available to treat muco-obstructive diseases. What are needed are effective, safe, and well-tolerated reducing agents for the treatment of diseases characterized by impaired mucus clearance.

SUMMARY OF THE INVENTION

One object of the present invention relates to a method to increase the liquefaction of mucus in a patient with excessive mucus or mucus with increased viscoelastic, cohesive, or adhesive properties. The method includes the step of contacting the mucus of a patient with abnormal or excessive mucus with a composition comprising a mucolytic compound containing a dithiol group to decrease mucus viscoelasticity through the reduction of mucin disulfide bonds.

It is an object of the present invention to provide mucolytic compounds that are more effective, and/or absorbed less rapidly from mucosal surfaces, and/or are better tolerated as compared to N-acetylcysteine (NAC).

It is another object of the present invention to provide compounds which are more active in the physiologic environment of the airway surface.

It is another object of the present invention to provide compounds that are more potent and/or absorbed less rapidly, as compared to compounds such as N-acetylcysteine.

Therefore, such compounds will give a prolonged pharmacodynamic half-life on mucosal surfaces as compared to NAC.

It is another object of the present invention to provide methods of treatment that take advantage of the pharmacological properties of the compounds described above.

In particular, it is an object of the present invention to provide methods of treatment which rely on promoting mucus clearance from mucosal surfaces.

It is an object of the present invention to provide compounds that are more potent and/or absorbed less rapidly from mucosal surfaces, and/or are less reversible as compared to known compounds.

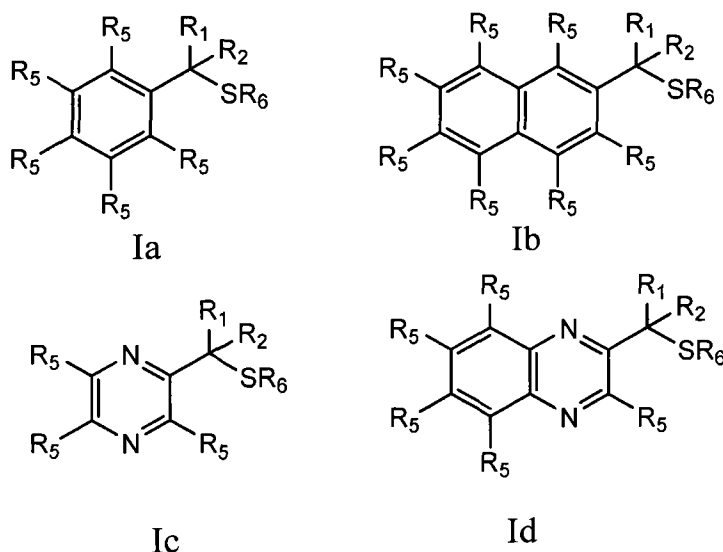
Therefore, the compounds will give a prolonged pharmacodynamic half-life on mucosal surfaces as compared to known compounds.

It is another object of the present invention to provide compounds which are (1) absorbed less rapidly from mucosal surfaces, especially airway surfaces, as compared to known compounds and; (2) It is another object of the present invention to provide compounds that are more potent and/or absorbed less rapidly and/or exhibit less reversibility, as compared to compounds such as NAC. Therefore, such compounds will give a prolonged pharmacodynamic half-life on mucosal surfaces as compared to previous compounds.

It is another object of the present invention to provide methods of treatment that take advantage of the pharmacological properties of the compounds described above.

In particular, it is an object of the present invention to provide methods of treatment which rely on rehydration of mucosal surfaces.

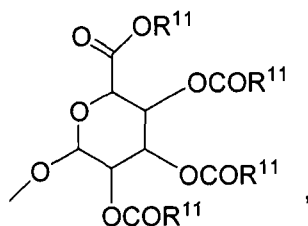
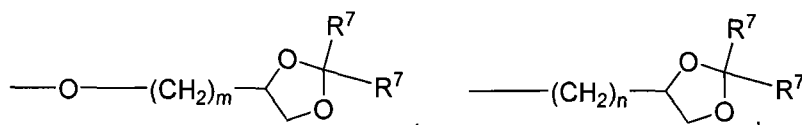
The objects of the present invention may be accomplished with a class of dithiols represented by compounds of Formula I which embraces structures (Ia)-(Id):



wherein

R^1 and R^2 are each, independently, hydrogen, lower alkyl, halogen, trifluoromethyl, hydroxyl-lower alkyl, phenyl, (phenyl)-lower alkyl, (halophenyl)-lower alkyl, ((lower-alkyl)phenyl)-lower-alkyl, ((lower-alkoxy)phenyl)-lower-alkyl, (naphthyl)-lower-alkyl, or (pyridyl)-lower-alkyl;

each R^5 is, independently, hydrogen, halogen, trifluoromethyl, lower alkyl, unsubstituted or substituted phenyl, lower alkyl-thio, phenyl-lower alkyl-thio, lower alkyl-sulfonyl, or phenyl-lower alkyl-sulfonyl, OH, $-(CH_2)_m-OR^8$, $-O-(CH_2)_m-OR^8$, $-(CH_2)_n-NR^7R^{10}$, $-(CH_2)_n-NR^7R^7$, $-(CH_2)_n-NR^{10}R^{10}$, $-O-(CH_2)_m-NR^7R^{10}$, $-O-(CH_2)_m-NR^7R^7$, $-O-(CH_2)_m-NR^{10}R^{10}$, $-(CH_2)_n(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-O-(CH_2)_m(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-(CH_2CH_2O)_m-R^8$, $-O-(CH_2CH_2O)_m-R^8$, $-(CH_2CH_2O)_m-CH_2CH_2NR^7R^{10}$, $-O-(CH_2CH_2O)_m-CH_2CH_2NR^7R^{10}$, $-(CH_2)_n-C(=O)NR^7R^{10}$, $-O-(CH_2)_m-C(=O)NR^7R^{10}$, $-(CH_2)_n-(Z)_g-R^7$, $-O-(CH_2)_m-(Z)_g-R^7$, $-(CH_2)_n-NR^{10}-CH_2(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-O-(CH_2)_m-NR^{10}-CH_2(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-(CH_2)_n-CO_2R^7$, $-O-(CH_2)_m-CO_2R^7$, $-OSO_3H$, $-O$ -glucuronide, $-O$ -glucose,



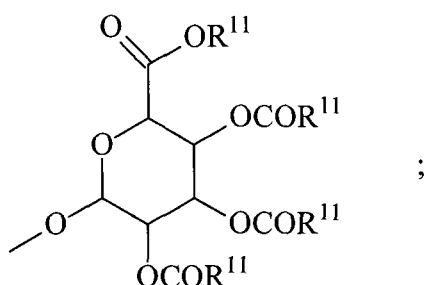
-Link-(CH₂)_m-CAP, -Link-(CH₂)_n(CHOR⁸)(CHOR⁸)_n-CAP, -Link-(CH₂CH₂O)_m-CH₂-CAP, -Link-(CH₂CH₂O)_m-CH₂CH₂-CAP, -Link-(CH₂)_m-(Z)_g-CAP, -Link-(CH₂)_n(Z)_g-(CH₂)_m-CAP, -Link-(CH₂)_n-NR¹³-CH₂(CHOR⁸)(CHOR⁸)_n-CAP, -Link-(CH₂)_n-(CHOR⁸)_mCH₂-NR¹³-(Z)_g-CAP, -Link-(CH₂)_n-NR¹³-(CH₂)_m(CHOR⁸)_nCH₂NR¹³-(Z)_g-CAP, -Link-(CH₂)_m-(Z)_g-(CH₂)_m-CAP, -Link-NH-C(=O)-NH-(CH₂)_m-CAP, -Link-(CH₂)_m-C(=O)NR¹³-(CH₂)_m-CAP, -Link-(CH₂)_n-(Z)_g-(CH₂)_m-(Z)_g-CAP, or -Link-Z_g-(CH₂)_m-Het-(CH₂)_m-CAP,

with the proviso that at least one R⁵ group contains at least one basic nitrogen;

each R⁶ is, independently, hydrogen, -C(=O)-R⁷, or an Amino Acyl of the natural amino acid configuration;

each R⁷ is, independently, hydrogen, lower alkyl, phenyl, substituted phenyl, lower alkyl phenyl, -CH₂(CHOR⁸)_m-CH₂OR⁸, 2-furyl or 3-furyl;

each R⁸ is, independently, hydrogen, lower alkyl, lower alkyl phenyl, -C(=O)-R¹¹, glucuronide, 2-tetrahydropyranyl, or



each R⁹ is, independently, -CO₂R⁷, -CON(R⁷)₂, -SO₂CH₃, -C(=O)R⁷, -CO₂R¹³, -CON(R¹³)₂, -SO₂CH₂R¹³, or -C(=O)R¹³;

each R¹⁰ is, independently, -H, -SO₂CH₃, -CO₂R⁷, -C(=O)NR⁷R⁹, -C(=O)R⁷, or -CH₂-(CHOH)_n-CH₂OH;

each Z is, independently, $-(\text{CHOH})-$, $-\text{C}(=\text{O})-$, $-(\text{CHNR}^7\text{R}^{10})-$, $-(\text{C}=\text{NR}^{10})-$, $-\text{NR}^{10}-$, $-(\text{CH}_2)_n-$, $-(\text{CHNR}^{13}\text{R}^{13})-$, $-(\text{C}=\text{NR}^{13})-$, or $-\text{NR}^{13}-$, $-\text{CO}_2\text{H}$;

each R^{11} is, independently, hydrogen, lower alkyl, phenyl lower alkyl or substituted phenyl lower alkyl;

each R^{12} is, independently, $-\text{SO}_2\text{CH}_3$, $-\text{CO}_2\text{R}^7$, $-\text{C}(=\text{O})-\text{NR}^7\text{R}^9$, $-\text{C}(=\text{O})-\text{R}^7$, $-\text{CH}_2(\text{CHOH})_n-\text{CH}_2\text{OH}$, $-\text{CO}_2\text{R}^{13}$, $-\text{C}(=\text{O})-\text{NR}^{13}\text{R}^{13}$, or $-\text{C}(=\text{O})\text{R}^{13}$;

each R^{13} is, independently, hydrogen, lower alkyl, phenyl, substituted phenyl or $-\text{CH}_2(\text{CHOR}^8)_m-\text{CH}_2\text{OR}^8$, $-\text{SO}_2\text{CH}_3$, $-\text{CO}_2\text{R}^7$, $-\text{C}(=\text{O})\text{NR}^7\text{R}^9$, $-\text{C}(=\text{O})-\text{R}^7$, $-\text{CH}_2-(\text{CHOH})_n-\text{CH}_2\text{OH}$, $-(\text{CH}_2)_m-\text{NR}^7\text{R}^{10}$, $-(\text{CH}_2)_m-\text{NR}^7\text{R}^7$, $-(\text{CH}_2)_m-\text{NR}^{11}\text{R}^{11}$, $-(\text{CH}_2)_m-(\text{NR}^{11}\text{R}^{11}\text{R}^{11})^+$, $-(\text{CH}_2)_m-(\text{CHOR}^8)_m-(\text{CH}_2)_m\text{NR}^{11}\text{R}^{11}$, $-(\text{CH}_2)_m-(\text{CHOR}^8)_m-(\text{CH}_2)_m\text{NR}^7\text{R}^{10}$, $-(\text{CH}_2)_m-\text{NR}^{10}\text{R}^{10}$, $-(\text{CH}_2)_m-(\text{CHOR}^8)_m-(\text{CH}_2)_m-(\text{NR}^{11}\text{R}^{11}\text{R}^{11})^+$, $-(\text{CH}_2)_m-(\text{CHOR}^8)_m-(\text{CH}_2)_m\text{NR}^7\text{R}^7$;

each g is, independently, an integer from 1 to 6;

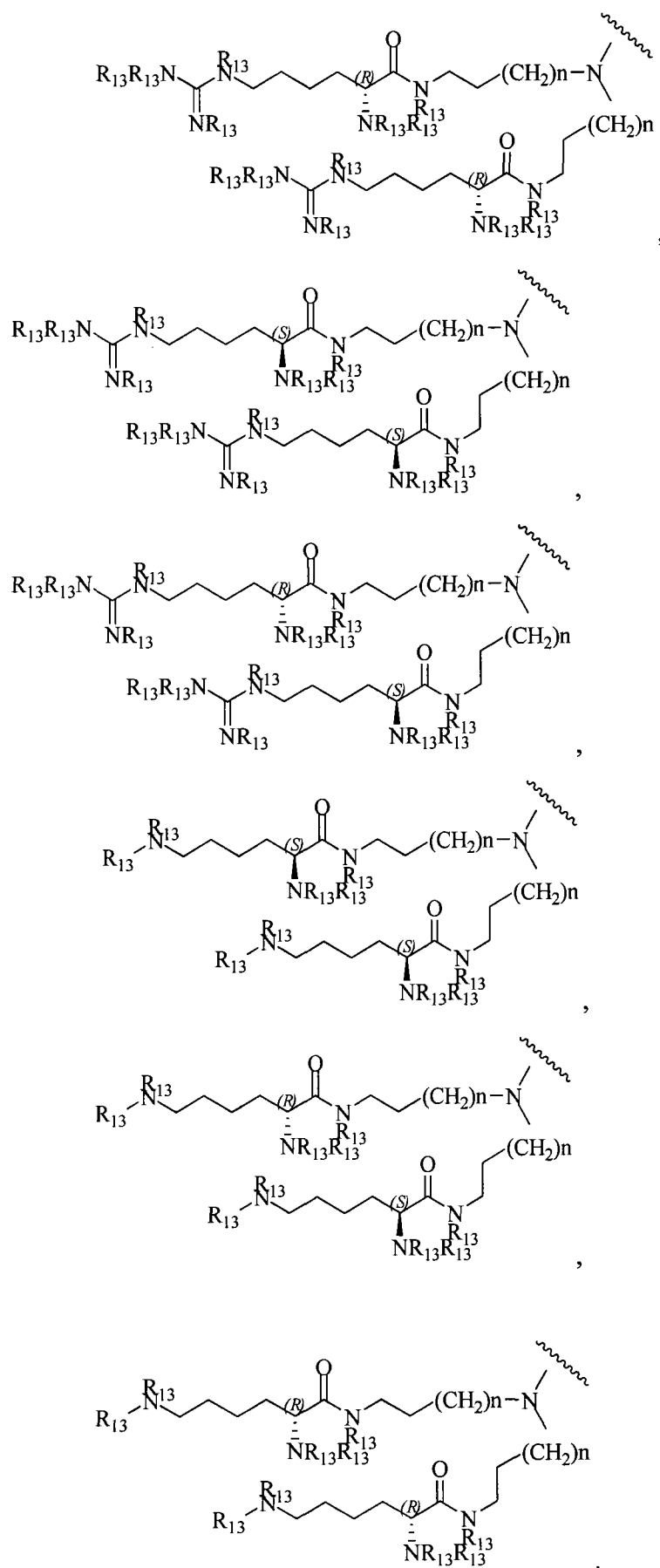
each m is, independently, an integer from 1 to 7;

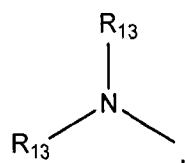
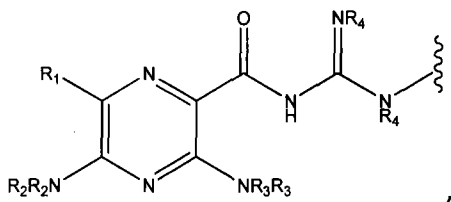
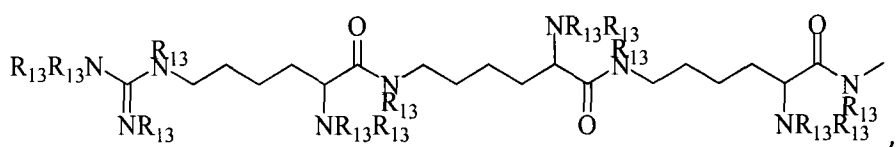
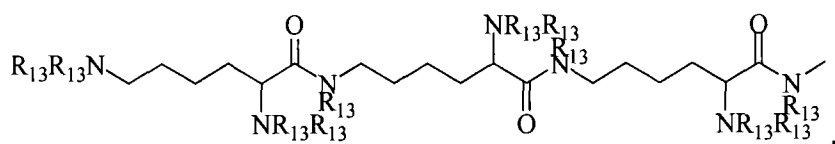
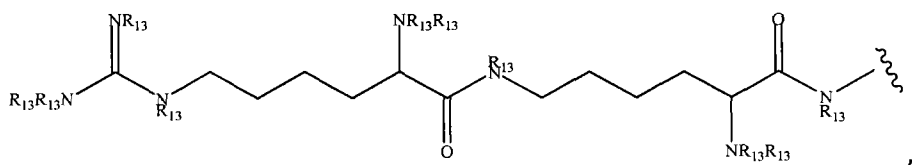
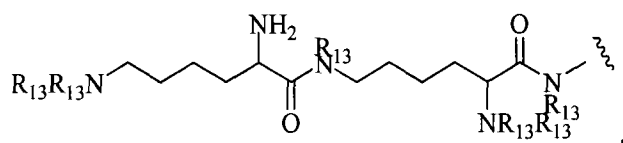
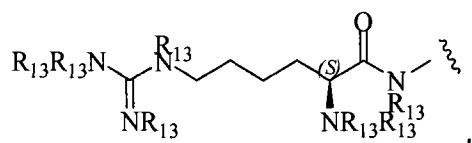
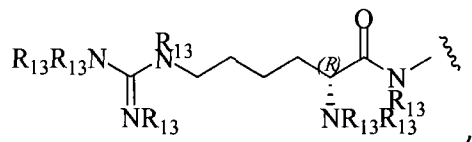
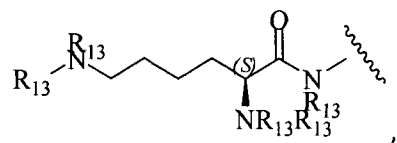
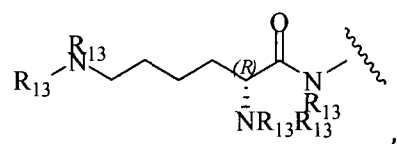
each n is, independently, an integer from 0 to 7;

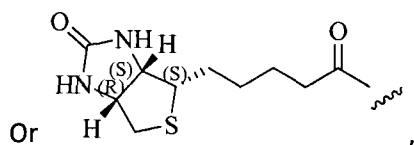
each $-\text{Het}-$ is, independently, $-\text{N}(\text{R}^7)-$, $-\text{N}(\text{R}^{10})-$, $-\text{S}-$, $-\text{SO}-$, $-\text{SO}_2-$, $-\text{O}-$, $-\text{SO}_2\text{NH}-$, $-\text{NH}\text{SO}_2-$, $-\text{NR}^7\text{CO}-$, $-\text{CONR}^7-$, $-\text{N}(\text{R}^{13})-$, $-\text{SO}_2\text{NR}^{13}-$, $-\text{NR}^{13}\text{CO}-$, or $-\text{CONR}^{13}-$;

each Link is, independently, $-\text{O}-$, $-(\text{CH}_2)_n-$, $-\text{O}(\text{CH}_2)_m-$, $-\text{NR}^{13}-\text{C}(=\text{O})-\text{NR}^{13}-$, $-\text{NR}^{13}-\text{C}(=\text{O})-(\text{CH}_2)_m-$, $-\text{C}(=\text{O})\text{NR}^{13}-(\text{CH}_2)_m-$, $-(\text{CH}_2)_n-(\text{Z})_g-(\text{CH}_2)_n-$, $-\text{S}-$, $-\text{SO}-$, $-\text{SO}_2-$, $-\text{SO}_2\text{NR}^7-$, $-\text{SO}_2\text{NR}^{10}-$, or $-\text{Het}-$;

each CAP is, independently:







with the proviso that when any $-\text{CHOR}^8$ - or $-\text{CH}_2\text{OR}^8$ groups are located 1,2- or 1,3- with respect to each other, the R^8 groups may, optionally, be taken together to form a cyclic mono- or di-substituted 1,3-dioxane or 1,3-dioxolane; and racemates, enantiomers, diastereomers, tautomers, polymorphs, pseudopolymorphs and pharmaceutically acceptable salts, thereof.

The present invention also provides pharmaceutical compositions which comprise a compound as described herein.

The present invention also provides a method of restoring mucosal defense, comprising:

contacting mucus with an effective amount of compound described herein to a subject in need thereof.

The present invention also provides a method of decreasing mucus viscoelasticity, comprising:

administering an effective amount of a compound described herein to a mucosal surface of a subject.

The present invention also provides a method of decreasing mucus viscoelasticity on a mucosal surface, comprising:

administering an effective amount of a compound described herein to a mucosal surface of a subject.

The present invention also provides a method of scavenging free radicals on a mucosal surface, comprising:

administering an effective amount of a compound described herein to a mucosal surface of a subject.

The present invention also provides a method of decreasing inflammation on a mucosal surface, comprising:

administering an effective amount of a compound described herein to a mucosal surface of a subject.

The present invention also provides a method of quenching oxidative free radicals on a mucosal surface, comprising:

administering an effective amount of a compound described herein to a mucosal surface of a subject.

The present invention also provides a method of reducing inflammatory cells on a mucosal surface, comprising:

administering an effective amount of a compound described herein to a mucosal surface of a subject.

The present invention also provides a method treating mucus obstructive diseases, comprising:

contacting mucus with an effective amount of compound described herein to a subject in need thereof.

The present invention also provides a method treating mucus adhesion, comprising:

contacting mucus with an effective amount of compound described herein to a subject in need thereof.

The present invention also provides a method of treating pulmonary fibrosis, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating chronic bronchitis, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating cystic fibrosis, comprising:

administering an effective amount of compound described herein to a subject in need thereof.

The present invention also provides a method of treating cystic fibrosis exacerbations, comprising:

administering an effective amount of compound described herein to a subject in need thereof.

The present invention also provides a method of treating pulmonary fibrosis, comprising:

administering an effective amount of compound described herein to a subject in need thereof.

The present invention also provides a method of treating bronchiectasis, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating chronic obstructive pulmonary disease, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating chronic obstructive pulmonary disease exacerbations, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating asthma, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating asthma exacerbations, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating esophagitis, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating ventilator-induced pneumonia, comprising:

administering an effective compound described herein to a subject by means of a ventilator.

The present invention also provides a method of treating primary ciliary dyskinesia, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating emphysema, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating pneumonia, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating rhinosinusitis, comprising:
administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating nasal dehydration, comprising:

administering an effective amount of a compound described herein to the nasal passages of a subject in need thereof.

In a specific embodiment, the nasal dehydration is brought on by administering dry oxygen to the subject.

The present invention also provides a method of treating sinusitis, comprising:
administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating constipation, comprising:
administering an effective amount of a compound described herein to a subject in need thereof. In one embodiment of this method, the compound is administered either orally or via a suppository or enema.

The present invention also provides a method of treating distal intestinal obstruction syndrome, comprising:

administering an effective amount of compound described herein to a subject in need thereof.

The present invention also provides a method of treating chronic diverticulitis comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of inducing sputum for diagnostic purposes, comprising:

administering an effective amount of compound described herein to a subject in need thereof.

The present invention also provides a method of treating inhaled pathogens, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating inhaled irritants, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

The present invention also provides a method of treating inhaled particles, comprising:

administering an effective amount of a compound described herein to a subject in need thereof.

In a specific embodiment, the inhaled particles are insoluble particles including dust, debris, or radioactive material.

The objects of the invention may also be accomplished with a method of treating anthrax, comprising administering an effective amount of a compound of Formula I as defined herein and an osmolyte to a subject in need thereof.

The objects of the invention may also be accomplished with a method of prophylactic, post-exposure prophylactic, preventive or therapeutic treatment against diseases or conditions caused by pathogens, particularly pathogens which may be used in bioterrorism, comprising administering an effective amount of a compound of Formula I to a subject in need thereof.

It is further an object of the present invention to provide treatments comprising the use of osmolytes together with mucolytics of Formula I that are more potent, more specific, and/or absorbed less rapidly from mucosal surfaces as compared to compounds such as NAC.

It is another aspect of the present invention to provide treatments using mucolytics of Formula I that are more potent and/or absorbed less rapidly and/or exhibit less reversibility, as compared to compounds such as NAC when administered with an osmotic enhancer. Therefore, such mucolytics when used in conjunction with osmolytes will give an increased pharmacodynamic effect on mucosal surfaces as compared to either compound used alone.

It is another object of the present invention to provide treatments using mucolytics of Formula I and osmolytes together which are absorbed less rapidly from mucosal surfaces, especially airway surfaces than NAC. It is another object of the invention to provide compositions which contain mucolytics of Formula I and osmolytes.

The objects of the invention may be accomplished with a method of treating a disease ameliorated by increased mucus clearance and mucosal hydration comprising administering an effective amount of a compound of Formula I as defined herein and an osmolyte to a subject in need of increased mucociliary clearance and/or mucosal hydration.

BRIEF DESCRIPTION OF THE DRAWINGS

- Figure 1. Role of mucus dehydration in pathogenic sequence of CF/COPD.
- Figure 2. Enhanced mucin reducing capabilities of Compound **76** relative to NAC.
- Figure 3. Modification of Compound **76** without loss of reducing activity.
- Figure 4. Reducing activity relative to compounds known in the art.
- Figure 5. Advantage of Compound **76** substitutions.
- Figure 6. Integrated assays to assess cell permeation and pro-inflammatory effects.
- Figure 7. Pro-drugs of Compound **86**.
- Figure 8. Metabolic activation of Compound **85** in COPD sputum.
- Figure 9. Mucus reduction on primary human bronchial epithelial (HBE) cultures.

DETAILED DESCRIPTION OF THE INVENTION

As used herein, the following terms are defined as indicated.

"A compound of the invention" means a compound of Formula I or a salt, particularly a pharmaceutically acceptable salt thereof.

"A compound of Formula I" means a compound having the structural formula designated herein as Formula I. Compounds of Formula I include solvates and hydrates (i.e., adducts of a compound of Formula I with a solvent). In those embodiments wherein a compound of Formula I includes one or more chiral centers, the phrase is intended to encompass each individual stereoisomer including optical isomers (enantiomers and diastereomers) and geometric isomers (cis-/trans-isomerism) and mixtures of stereoisomers. In addition, compounds of Formula I also include tautomers of the depicted formula(s).

Throughout the description and examples, compounds are named using standard IUPAC naming principles, where possible, including the use of the ChemDraw Ultra 11.0 software program for naming compounds, sold by CambridgeSoft Corp./PerkinElmer.

In some chemical structure representations where carbon atoms do not have a sufficient number of attached variables depicted to produce a valence of four, the remaining carbon substituents needed to provide a valence of four should be assumed to be hydrogen. Similarly, in some chemical structures where a bond is drawn without specifying the terminal group, such bond is indicative of a methyl (Me, -CH₃) group, as is conventional in the art.

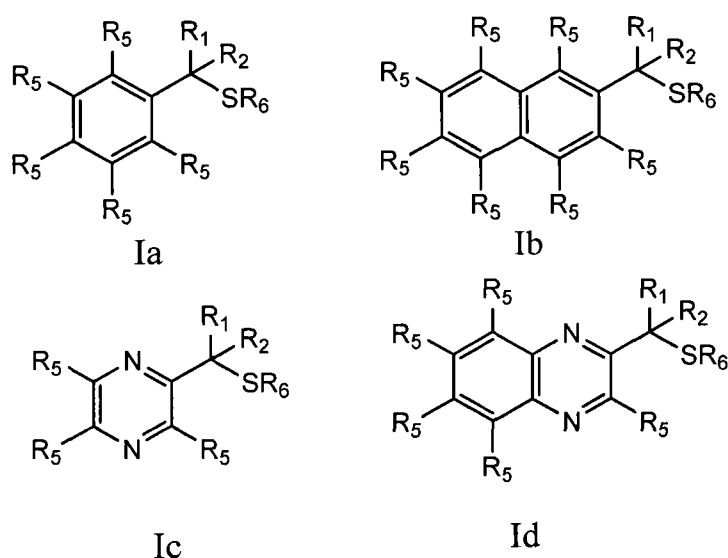
The present invention is based on the discovery that the compounds of Formula I are more potent and/or, absorbed less rapidly, achieve higher concentrations and have higher residence time in the mucosal surfaces, especially airway surfaces, and/or are better tolerated

compared to NAC and DTT. Therefore, the compounds of Formula I have a greater activity and/or produce less cellular toxicity on mucosal surfaces as compared to NAC.

The present invention is based on the discovery that the compounds of formula (I) are more potent and/or, absorbed less rapidly from mucosal surfaces, especially airway surfaces, and/or less reversible from interactions as compared to compounds such as NAC.

Therefore, the compounds of formula (I) have a longer half-life on mucosal surfaces as compared to these compounds.

In the compounds represented by formula I which embraces structures (Ia)-(Id):

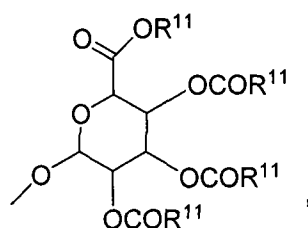
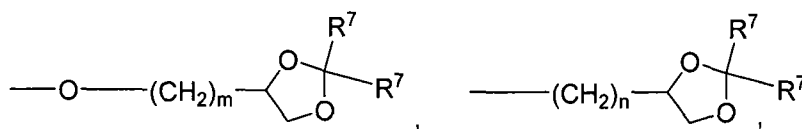


wherein R^1 and R^2 are each, independently, hydrogen, lower alkyl, halogen, trifluoromethyl, hydroxyl-lower alkyl, phenyl, (phenyl)-lower alkyl, (halophenyl)-lower alkyl, ((lower-alkyl)phenyl)-lower-alkyl, ((lower-alkoxy)phenyl)-lower-alkyl, (naphthyl)-lower-alkyl, or (pyridyl)-lower-alkyl;

R^3 and R^4 are each, independently, hydrogen, lower alkyl, hydroxyl-lower alkyl, phenyl, (phenyl)-lower alkyl, (halophenyl)-lower alkyl, ((lower-alkyl)phenyl)-lower-alkyl, ((lower-alkoxy)phenyl)-lower-alkyl, (naphthyl)-lower-alkyl, or (pyridyl)-lower-alkyl;

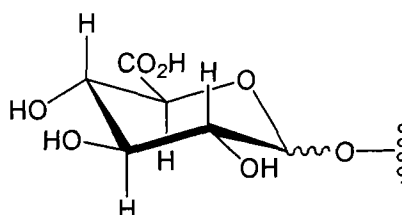
each R^5 is, independently, hydrogen, halogen, trifluoromethyl, lower alkyl, unsubstituted or substituted phenyl, lower alkyl-thio, phenyl-lower alkyl-thio, lower alkyl-sulfonyl, or phenyl-lower alkyl-sulfonyl, OH, $-(CH_2)_m-OR^8$, $-O-(CH_2)_m-OR^8$, $-(CH_2)_n-NR^7R^{10}$, $-(CH_2)_n-NR^7R^7$, $-(CH_2)_n-NR^7R^7$, $-O-(CH_2)_m-NR^7R^{10}$, $-O-(CH_2)_m-NR^7R^7$, $-O-(CH_2)_m-NR^7R^7$, $-(CH_2)_n(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-O-(CH_2)_m(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-(CH_2CH_2O)_m-R^8$, $-O-(CH_2CH_2O)_m-R^8$, $-(CH_2CH_2O)_m-CH_2CH_2NR^7R^{10}$, $-O-(CH_2CH_2O)_m-$

$\text{CH}_2\text{CH}_2\text{NR}^7\text{R}^{10}$, $-(\text{CH}_2)_n-\text{C}(=\text{O})\text{NR}^7\text{R}^{10}$, $-\text{O}-(\text{CH}_2)_m-\text{C}(=\text{O})\text{NR}^7\text{R}^{10}$, $-(\text{CH}_2)_n-(\text{Z})_g-\text{R}^7$, $-\text{O}-(\text{CH}_2)_m-(\text{Z})_g-\text{R}^7$, $-(\text{CH}_2)_n-\text{NR}^{10}-\text{CH}_2(\text{CHOR}^8)(\text{CHOR}^8)_n-\text{CH}_2\text{OR}^8$, $-\text{O}-(\text{CH}_2)_m-\text{NR}^{10}-\text{CH}_2(\text{CHOR}^8)(\text{CHOR}^8)_n-\text{CH}_2\text{OR}^8$, $-(\text{CH}_2)_n-\text{CO}_2\text{R}^7$, $-\text{O}-(\text{CH}_2)_m-\text{CO}_2\text{R}^7$, $-\text{OSO}_3\text{H}$, $-\text{O}$ -glucuronide, $-\text{O}$ -glucose,



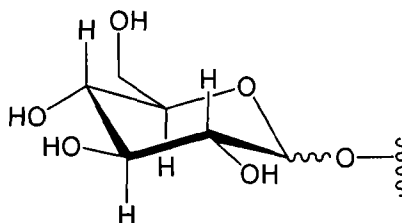
$-\text{Link}-(\text{CH}_2)_m-\text{CAP}$, $-\text{Link}-(\text{CH}_2)_n(\text{CHOR}^8)(\text{CHOR}^8)_n-\text{CAP}$, $-\text{Link}-(\text{CH}_2\text{CH}_2\text{O})_m-\text{CH}_2-\text{CAP}$, $-\text{Link}-(\text{CH}_2\text{CH}_2\text{O})_m-\text{CH}_2\text{CH}_2-\text{CAP}$, $-\text{Link}-(\text{CH}_2)_m-(\text{Z})_g-\text{CAP}$, $-\text{Link}-(\text{CH}_2)_n(\text{Z})_g-(\text{CH}_2)_m-\text{CAP}$, $-\text{Link}-(\text{CH}_2)_n-\text{NR}^{13}-\text{CH}_2(\text{CHOR}^8)(\text{CHOR}^8)_n-\text{CAP}$, $-\text{Link}-(\text{CH}_2)_n-(\text{CHOR}^8)_m\text{CH}_2-\text{NR}^{13}-(\text{Z})_g-\text{CAP}$, $-\text{Link}-(\text{CH}_2)_n\text{NR}^{13}-(\text{CH}_2)_m(\text{CHOR}^8)_n\text{CH}_2\text{NR}^{13}-(\text{Z})_g-\text{CAP}$, $-\text{Link}-(\text{CH}_2)_m-(\text{Z})_g-(\text{CH}_2)_m-\text{CAP}$, $-\text{Link}-\text{NH}-\text{C}(=\text{O})-\text{NH}-(\text{CH}_2)_m-\text{CAP}$, $-\text{Link}-(\text{CH}_2)_m-\text{C}(=\text{O})\text{NR}^{13}-(\text{CH}_2)_m-\text{CAP}$, $-\text{Link}-(\text{CH}_2)_n-(\text{Z})_g-(\text{CH}_2)_m-(\text{Z})_g-\text{CAP}$, or $-\text{Link}-\text{Z}_g-(\text{CH}_2)_m-\text{Het}-(\text{CH}_2)_m-\text{CAP}$ with the proviso that at least one R^5 group contains at least one basic nitrogen;

The term $-\text{O}$ -glucuronide, unless otherwise specified, means a group represented by



wherein the $\sim\text{O}$ means the glycosidic linkage can be above or below the plane of the ring.

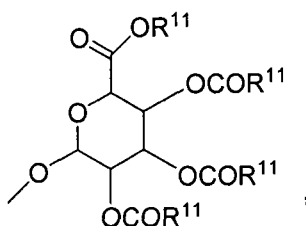
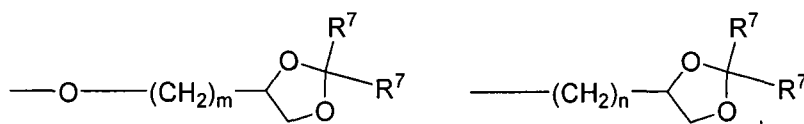
The term $-\text{O}$ -glucose, unless otherwise specified, means a group represented by



wherein the $\sim\text{O}$ means the glycosidic linkage can be above or below the plane of the ring.

In a preferred embodiment of the present invention, R^5 is one of the following:

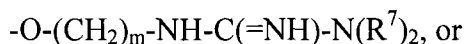
hydrogen, halogen, trifluoromethyl, lower alkyl, unsubstituted or substituted phenyl, lower alkyl-thio, phenyl-lower alkyl-thio, lower alkyl-sulfonyl, or phenyl-lower alkyl-sulfonyl, OH, $-(CH_2)_m-OR^8$, $-O-(CH_2)_m-OR^8$, $-(CH_2)_n-NR^7R^{10}$, $-O-(CH_2)_m-NR^7R^{10}$, $-(CH_2)_n-NR^{10}R^{10}$, $-(CH_2)_n(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-O-(CH_2)_m(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-(CH_2CH_2O)_m-R^8$, $-O-(CH_2CH_2O)_m-R^8$, $-(CH_2CH_2O)_m-CH_2CH_2NR^7R^{10}$, $-O-(CH_2)_m-NR^{10}R^{10}$, $-O-(CH_2CH_2O)_m-CH_2CH_2NR^7R^{10}$, $-(CH_2)_n-C(=O)NR^7R^{10}$, $-O-(CH_2)_m-C(=O)NR^7R^{10}$, $-(CH_2)_n-(Z)_g-R^7$, $-O-(CH_2)_m-(Z)_g-R^7$, $-(CH_2)_n-NR^{10}-CH_2(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-O-(CH_2)_m-NR^{10}-CH_2(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-(CH_2)_n-CO_2R^7$, $-O-(CH_2)_m-CO_2R^7$, $-OSO_3H$, $-O$ -glucuronide, $-O$ -glucose,



In a preferred embodiment, each $-(CH_2)_n-(Z)_g-R^7$ falls within the scope of the structures described above and is, independently,



In another preferred embodiment, each $-O-(CH_2)_m-(Z)_g-R^7$ falls within the scope of the structures described above and is, independently,



In another preferred embodiment, R^5 is $-OH$, $-O-(CH_2)_m(Z)_gR^{12}$, $-Het-(CH_2)_m-NH-C(=NR^{13})-NR^{13}R^{13}$, $-Het-(CH_2)_n-(Z)_g-(CH_2)_mNH-C(=NR^{13})-NR^{13}R^{13}$, $-Link-(CH_2)_m-(Z)_g-$

$(\text{CH}_2)_m\text{-CAP}$, $\text{Link-(CH}_2)_n\text{-CR}^{11}\text{R}^{11}\text{-CAP}$, $\text{-Het-(CH}_2)_m\text{-CONR}^{13}\text{R}^{13}$, $\text{-(CH}_2)_n\text{-NR}^{12}\text{R}^{12}$, $\text{-O-(CH}_2)_m\text{NR}^{11}\text{R}^{11}$, $\text{-O-(CH}_2)_m\text{-N}^\oplus\text{-(R}^{11})_3$, $\text{-(CH}_2)_n\text{-(Z)}_g\text{-(CH}_2)_m\text{-NR}^{10}\text{R}^{10}$, $\text{-Het-(CH}_2)_m\text{-(Z)}_g\text{-NH-C(=NR}^{13})\text{-NR}^{13}\text{R}^{13}$, $\text{-O-(CH}_2)_m\text{(CHOR}^8\text{)(CHOR}^8\text{)}_n\text{-CH}_2\text{OR}^8$, $\text{-O-(CH}_2)_m\text{-C(=O)NR}^7\text{R}^{10}$, $\text{-O-(CH}_2)_m\text{-(Z)}_g\text{-R}^7$, or $\text{-O-(CH}_2)_m\text{-NR}^{10}\text{-CH}_2\text{(CHOR}^8\text{)(CHOR}^8\text{)}_n\text{-CH}_2\text{OR}^8$.

In a particularly preferred embodiment, R^5 is $\text{-Link-(CH}_2)_m\text{-CAP}$, $\text{-Link-(CH}_2)_n\text{(CHOR}^8\text{)(CHOR}^8\text{)}_n\text{-CAP}$, $\text{-Link-(CH}_2\text{CH}_2\text{O)}_m\text{-CH}_2\text{-CAP}$, $\text{-Link-(CH}_2\text{CH}_2\text{O)}_m\text{-CH}_2\text{CH}_2\text{-CAP}$, $\text{-Link-(CH}_2)_m\text{-(Z)}_g\text{-CAP}$, $\text{-Link-(CH}_2)_n\text{(Z)}_g\text{-(CH}_2)_m\text{-CAP}$, $\text{-Link-(CH}_2)_n\text{-NR}^{13}\text{-CH}_2\text{(CHOR}^8\text{)(CHOR}^8\text{)}_n\text{-CAP}$, $\text{-Link-(CH}_2)_n\text{-(CHOR}^8\text{)}_m\text{CH}_2\text{-NR}^{13}\text{-(Z)}_g\text{-CAP}$, $\text{-Link-(CH}_2)_n\text{NR}^{13}\text{-(CH}_2)_m\text{(CHOR}^8\text{)}_n\text{CH}_2\text{NR}^{13}\text{-(Z)}_g\text{-CAP}$, $\text{-Link-(CH}_2)_m\text{-(Z)}_g\text{-(CH}_2)_m\text{-CAP}$, $\text{-Link-NH-C(=O)-NH-(CH}_2)_m\text{-CAP}$, $\text{-Link-(CH}_2)_m\text{-C(=O)NR}^{13}\text{-(CH}_2)_m\text{-CAP}$, $\text{-Link-(CH}_2)_n\text{-(Z)}_g\text{-(CH}_2)_m\text{-(Z)}_g\text{-CAP}$, or $\text{-Link-Z}_g\text{-(CH}_2)_m\text{-Het-(CH}_2)_m\text{-CAP}$.

In another particularly preferred embodiment, R^5 is $\text{-O-(CH}_2)_m\text{-NR}^{10}\text{R}^{10}$, $\text{-O-(CH}_2)_m\text{-NR}^7\text{R}^{10}$, $\text{-(CH}_2)_n\text{-NR}^7\text{R}^{10}\text{-(CH}_2)_n\text{-NR}^{10}\text{R}^{10}$, $\text{-(CH}_2)_n\text{-NR}^7\text{R}^7$, $\text{-O-(CH}_2)_m\text{-NR}^7\text{R}^{10}$.

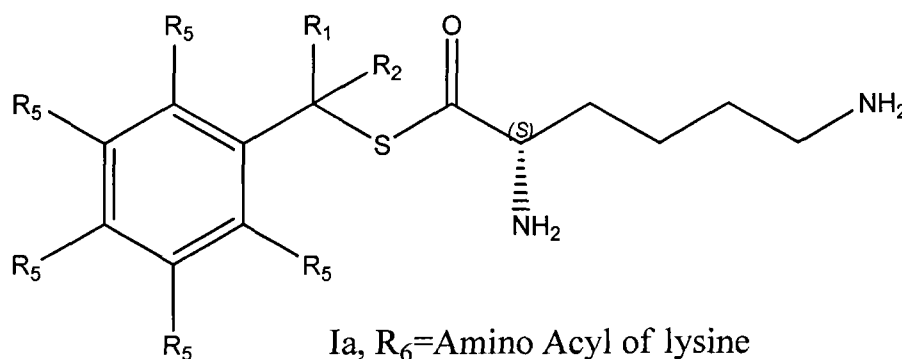
each R^6 is, independently, hydrogen, -C(=O)-R^7 , or an Amino Acyl of the natural amino acid configuration;

In a preferred embodiment, R^6 is H, isobutyl, propionyl, or 2-furyl.

In a particularly preferred embodiment, R^6 is acetyl.

In another preferred embodiment, R^6 is $\text{-(C=O)-CHNH}_2\text{-(CH}_2)_4\text{NH}_2$.

Amino Acyl of the natural amino acid configuration refers to the twenty natural occurring amino acids comprised of glycine, alanine, valine, leucine, isoleucine, cysteine, methionine, phenylalanine, tyrosine, tryptophan, proline, serine, threonine, asparagine, glutamine, aspartic acid, glutamic acid, histidine, lysine, or arginine. For example, the structure of a compound of Formula Ia using R^6 = Amino Acyl of lysine is as follows:



each R^7 is, independently, hydrogen, lower alkyl, phenyl, substituted phenyl, lower alkyl phenyl, $\text{-CH}_2\text{(CHOR}^8\text{)}_m\text{-CH}_2\text{OR}^8$; 2-furyl or 3-furyl;

In a preferred embodiment, R^7 is isopropyl, ethyl, or 2-furyl.

In a particularly preferred embodiment, R^7 is H or methyl.

Selected substituents within the compounds of the invention are present to a recursive degree. In this context, "recursive substituent" means that a substituent may recite another instance of itself. Because of the recursive nature of such substituents, theoretically, a large number of compounds may be present in any given embodiment. For example, R^9 contains a R^{13} substituent. R^{13} can contain an R^{10} substituent and R^{10} can contain a R^9 substituent. One of ordinary skill in the art of medicinal chemistry understands that the total number of such substituents is reasonably limited by the desired properties of the compound intended. Such properties include, by way of example and not limitation, physical properties such as molecular weight, solubility or log P, application properties such as activity against the intended target, and practical properties such as ease of synthesis.

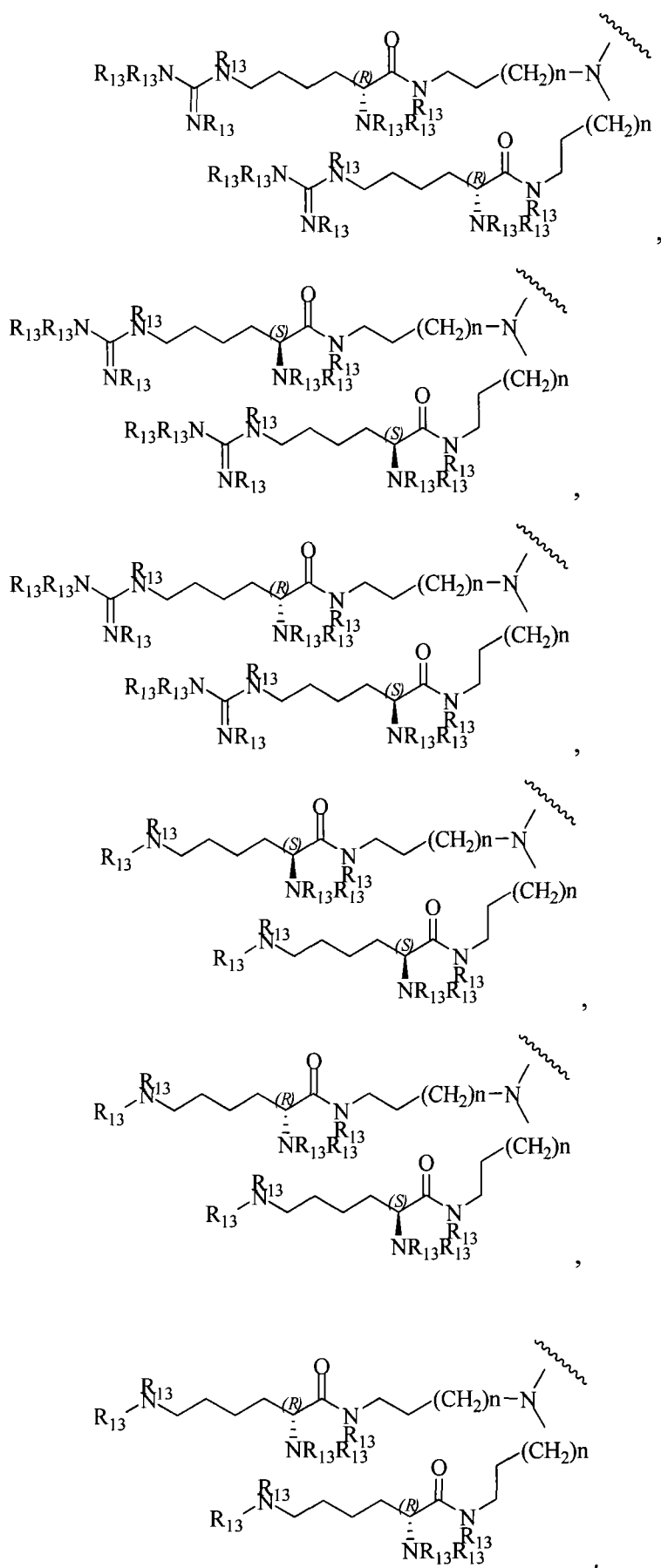
By way of example and not limitation, R^5 , R^{13} and R^{10} are recursive substituents in certain embodiments. Typically, each of these may independently occur 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, or 0, times in a given embodiment. More typically, each of these may independently occur 12 or fewer times in a given embodiment. More typically yet, R^9 will occur 0 to 8 times in a given embodiment, R^{13} will occur 0 to 6 times in a given embodiment and R^{10} will occur 0 to 6 times in a given embodiment. Even more typically yet, R^9 will occur 0 to 6 times in a given embodiment, R^{13} will occur 0 to 4 times in a given embodiment and R^{10} will occur 0 to 4 times in a given embodiment.

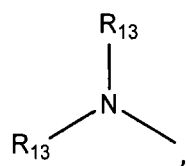
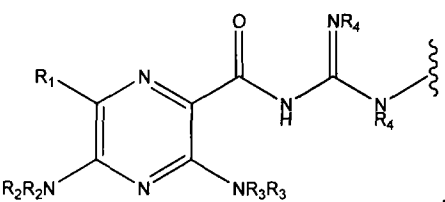
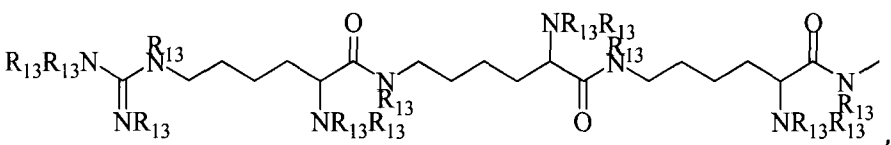
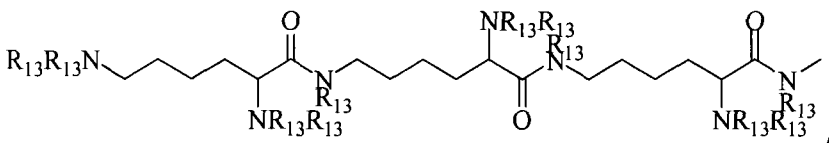
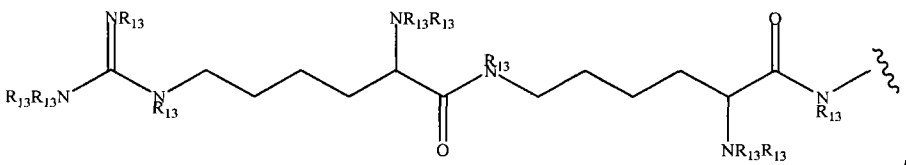
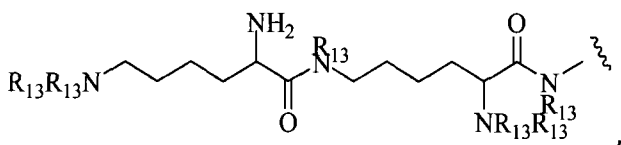
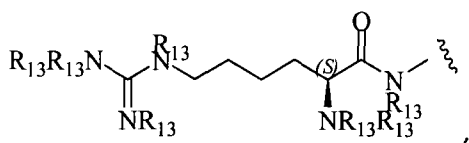
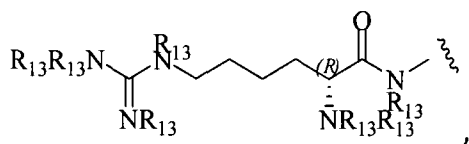
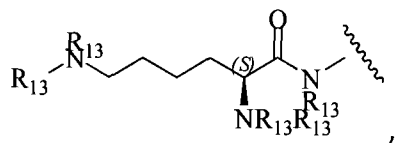
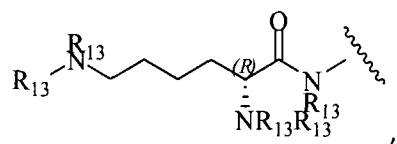
Recursive substituents are an intended aspect of the invention. One of ordinary skill in the art of medicinal chemistry understands the versatility of such substituents. To the degree that recursive substituents are present in an embodiment of the invention, the total number will be determined as set forth above.

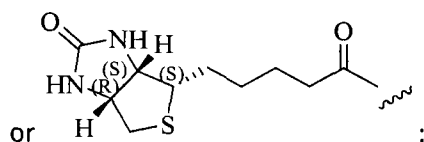
Each -Het- is, independently, $-N(R^7)-$, $-N(R^{10})-$, $-S-$, $-SO-$, $-SO_2-$, $-O-$, $-SO_2NH-$, $-NHSO_2-$, $-NR^7CO-$, $-CONR^7-$, $-N(R^{13})-$, $-SO_2NR^{13}-$, $-NR^{13}CO-$, or $-CONR^{13}-$. In a preferred embodiment, -Het- is $-O-$, $-N(R^7)-$, or $-N(R^{10})-$. Most preferably, -Het- is $-O-$.

Each -Link- is, independently, $-O-$, $-(CH_2)_n-$, $-O(CH_2)_m-$, $-NR^{13}-C(=O)-NR^{13}-$, $-NR^{13}-C(=O)-(CH_2)_m-$, $-C(=O)NR^{13}-(CH_2)_m-$, $-(CH_2)_n-(Z)_g-(CH_2)_n-$, $-S-$, $-SO-$, $-SO_2-$, $-SO_2NR^7-$, $-SO_2NR^{10}-$, or -Het-. In a preferred embodiment, -Link- is $-O-$, $-(CH_2)_n-$, $-NR^{13}-C(=O)-$, $(CH_2)_m-$, or $-C(=O)NR^{13}-(CH_2)_m-$.

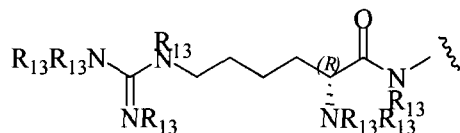
Each -CAP is each CAP is, independently
each CAP is, independently







In a preferred embodiment, CAP is



Each g is, independently, an integer from 1 to 6. Therefore, each g may be 1, 2, 3, 4, 5, or 6.

Each m is an integer from 1 to 7. Therefore, each m may be 1, 2, 3, 4, 5, 6, or 7.

Each n is an integer from 0 to 7. Therefore, each n may be 0, 1, 2, 3, 4, 5, 6, or 7.

Each Z is, independently, $-(\text{CHOH})-$, $-\text{C}(=\text{O})-$, $-(\text{CHNR}^7\text{R}^{10})-$, $-(\text{C}=\text{NR}^{10})-$, $-\text{NR}^{10}-$, $-(\text{CH}_2)_n-$, $-(\text{CHNR}^{13}\text{R}^{13})-$, $-(\text{C}=\text{NR}^{13})-$, or $-\text{NR}^{13}-$, or CO_2H . As designated by $(Z)_g$ in certain embodiments, Z may occur one, two, three, four, five or six times and each occurrence of Z is, independently, $-(\text{CHOH})-$, $-\text{C}(=\text{O})-$, $-(\text{CHNR}^7\text{R}^{10})-$, $-(\text{C}=\text{NR}^{10})-$, $-\text{NR}^{10}-$, $-(\text{CH}_2)_n-$, $-(\text{CHNR}^{13}\text{R}^{13})-$, $-(\text{C}=\text{NR}^{13})-$, or $-\text{NR}^{13}-$. Therefore, by way of example and not by way of limitation, $(Z)_g$ can be $-(\text{CHOH})-(\text{CHNR}^7\text{R}^{10})-$, $-(\text{CHOH})-(\text{CHNR}^7\text{R}^{10})-\text{C}(=\text{O})-$, $-(\text{CHOH})-(\text{CHNR}^7\text{R}^{10})-\text{C}(=\text{O})-(\text{CH}_2)_n-$, $-(\text{CHOH})-(\text{CHNR}^7\text{R}^{10})-\text{C}(=\text{O})-(\text{CH}_2)_n-(\text{CHNR}^{13}\text{R}^{13})-$, $-(\text{CHOH})-(\text{CHNR}^7\text{R}^{10})-\text{C}(=\text{O})-(\text{CH}_2)_n-(\text{CHNR}^{13}\text{R}^{13})-\text{C}(=\text{O})-$, and the like.

In any variable containing $-\text{CHOR}^8-$ or $-\text{CH}_2\text{OR}^8$ groups, when any $-\text{CHOR}^8-$ or $-\text{CH}_2\text{OR}^8$ groups are located 1,2- or 1,3- with respect to each other, the R^8 groups may, optionally, be taken together to form a cyclic mono- or di-substituted 1,3-dioxane or 1,3-dioxolane.

The compounds described herein may be prepared and used as the free base.

Alternatively, the compounds may be prepared and used as a pharmaceutically acceptable salt. Pharmaceutically acceptable salts are salts that retain or enhance the desired biological activity of the parent compound and do not impart undesired toxicological effects. Examples of such salts are (a) acid addition salts formed with inorganic acids, for example, hydrochloric acid, hydrobromic acid, sulfuric acid, phosphoric acid, nitric acid and the like; (b) salts formed with organic acids such as, for example, acetic acid, oxalic acid, tartaric acid, succinic acid, maleic acid, fumaric acid, gluconic acid, citric acid, malic acid, ascorbic acid, benzoic acid, tannic acid, palmitic acid, alginic acid, polyglutamic acid, naphthalenesulfonic

acid, methanesulfonic acid, p-toluenesulfonic acid, naphthalenedisulfonic acid, polygalacturonic acid, malonic acid, sulfosalicylic acid, glycolic acid, 2-hydroxy-3-naphthoate, pamoate, salicylic acid, stearic acid, phthalic acid, mandelic acid, lactic acid and the like; and (c) salts formed from elemental anions for example, chlorine, bromine, and iodine.

It is to be noted that all enantiomers, diastereomers, and racemic mixtures, tautomers, polymorphs, pseudopolymorphs and pharmaceutically acceptable salts of compounds within the scope of formulae I (Ia-Id) are embraced by the present invention. All mixtures of such enantiomers and diastereomers are within the scope of the present invention.

A compound of formula I and its pharmaceutically acceptable salts may exist as different polymorphs or pseudopolymorphs. As used herein, crystalline polymorphism means the ability of a crystalline compound to exist in different crystal structures. The crystalline polymorphism may result from differences in crystal packing (packing polymorphism) or differences in packing between different conformers of the same molecule (conformational polymorphism). As used herein, crystalline pseudopolymorphism means the ability of a hydrate or solvate of a compound to exist in different crystal structures. The pseudopolymorphs of the instant invention may exist due to differences in crystal packing (packing pseudopolymorphism) or due to differences in packing between different conformers of the same molecule (conformational pseudopolymorphism). The instant invention comprises all polymorphs and pseudopolymorphs of the compounds of formula I-III and their pharmaceutically acceptable salts.

A compound of formula I and its pharmaceutically acceptable salts may also exist as an amorphous solid. As used herein, an amorphous solid is a solid in which there is no long-range order of the positions of the atoms in the solid. This definition applies as well when the crystal size is two nanometers or less. Additives, including solvents, may be used to create the amorphous forms of the instant invention. The instant invention comprises all amorphous forms of the compounds of formula I-III and their pharmaceutically acceptable salts.

The compounds of formula I may exist in different tautomeric forms. One skilled in the art will recognize that amidines, amides, guanidines, ureas, thioureas, heterocycles and the like can exist in tautomeric forms. All possible tautomeric forms of the amidines, amides, guanidines, ureas, thioureas, heterocycles and the like of all of the embodiments of formula I are within the scope of the instant invention.

"Enantiomers" refer to two stereoisomers of a compound which are non-superimposable mirror images of one another.

Stereochemical definitions and conventions used herein generally follow S. P. Parker, Ed., *McGraw-Hill Dictionary of Chemical Terms* (1984) McGraw-Hill Book Company, New York; and Eliel, E. and Wilen, S., *Stereochemistry of Organic Compounds* (1994) John Wiley & Sons, Inc., New York. Many organic compounds exist in optically active forms, i.e., they have the ability to rotate the plane of plane-polarized light. In describing an optically active compound, the prefixes D and L or R and S are used to denote the absolute configuration of the molecule about its chiral center(s). The prefixes d and l, D and L, or (+) and (-) are employed to designate the sign of rotation of plane-polarized light by the compound, with S, (-), or l meaning that the compound is levorotatory while a compound prefixed with R, (+), or d is dextrorotatory. For a given chemical structure, these stereoisomers are identical except that they are mirror images of one another. A specific stereoisomer may also be referred to as an enantiomer, and a mixture of such isomers is often called an enantiomeric mixture. A 50:50 mixture of enantiomers is referred to as a racemic mixture or a racemate, which may occur where there has been no stereoselection or stereospecificity in a chemical reaction or process. The terms "racemic mixture" and "racemate" refer to an equimolar mixture of two enantiomeric species, devoid of optical activity.

A single stereoisomer, e.g. an enantiomer, substantially free of its stereoisomer may be obtained by resolution of the racemic mixture using a method such as formation of diastereomers using optically active resolving agents ("*Stereochemistry of Carbon Compounds*," (1962) by E. L. Eliel, McGraw Hill; Lochmuller, C. H., (1975) *J. Chromatogr.*, 113:(3) 283-302). Racemic mixtures of chiral compounds of the invention can be separated and isolated by any suitable method, including: (1) formation of ionic, diastereomeric salts with chiral compounds and separation by fractional crystallization or other methods, (2) formation of diastereomeric compounds with chiral derivatizing reagents, separation of the diastereomers, and conversion to the pure stereoisomers, and (3) separation of the substantially pure or enriched stereoisomers directly under chiral conditions.

"Diastereomer" refers to a stereoisomer with two or more centers of chirality and whose molecules are not mirror images of one another. Diastereomers have different physical properties, e.g. melting points, boiling points, spectral properties, and reactivities. Mixtures of diastereomers may separate under high resolution analytical procedures such as electrophoresis and chromatography.

Without being limited to any particular theory, it is believed that the compounds of formula (I), formula II, or formula III function *in vivo* as biological reducing. By blocking epithelial sodium channels present in mucosal surfaces the compounds of formula (I), formula II, or

formula III reduce the absorption of water by the mucosal surfaces. This effect increases the volume of protective liquids on mucosal surfaces, rebalances the system, and thus treats disease.

The compounds described herein may be prepared and used as the free base. Alternatively, the compounds may be prepared and used as a pharmaceutically acceptable salt. Pharmaceutically acceptable salts are salts that retain or enhance the desired biological activity of the parent compound and do not impart undesired toxicological effects. Examples of such salts are (a) acid addition salts formed with inorganic acids, for example, hydrochloric acid, hydrobromic acid, sulfuric acid, phosphoric acid, nitric acid and the like; (b) salts formed with organic acids such as, for example, acetic acid, oxalic acid, tartaric acid, succinic acid, maleic acid, fumaric acid, gluconic acid, citric acid, malic acid, ascorbic acid, benzoic acid, tannic acid, palmitic acid, alginic acid, polyglutamic acid, naphthalenesulfonic acid, methanesulfonic acid, p-toluenesulfonic acid, naphthalenedisulfonic acid, polygalacturonic acid, malonic acid, sulfosalicylic acid, glycolic acid, 2-hydroxy-3-naphthoate, pamoate, salicylic acid, stearic acid, phthalic acid, mandelic acid, lactic acid and the like; and (c) salts formed from elemental anions for example, chlorine, bromine, and iodine.

It is to be noted that all enantiomers, diastereomers, and racemic mixtures, tautomers, polymorphs, pseudopolymorphs and pharmaceutically acceptable salts of compounds within the scope of formulae (X) are embraced by the present invention. All mixtures of such enantiomers and diastereomers are within the scope of the present invention.

A compound of formula I and its pharmaceutically acceptable salts may exist as different polymorphs or pseudopolymorphs. As used herein, crystalline polymorphism means the ability of a crystalline compound to exist in different crystal structures. The crystalline polymorphism may result from differences in crystal packing (packing polymorphism) or differences in packing between different conformers of the same molecule (conformational polymorphism). As used herein, crystalline pseudopolymorphism means the ability of a hydrate or solvate of a compound to exist in different crystal structures. The pseudopolymorphs of the instant invention may exist due to differences in crystal packing (packing pseudopolymorphism) or due to differences in packing between different conformers of the same molecule (conformational pseudopolymorphism). The instant invention comprises all polymorphs and pseudopolymorphs of the compounds of formula I-III and their pharmaceutically acceptable salts.

A compound of formula I and its pharmaceutically acceptable salts may also exist as an amorphous solid. As used herein, an amorphous solid is a solid in which there is no long-range order of the positions of the atoms in the solid. This definition applies as well when the crystal size is two nanometers or less. Additives, including solvents, may be used to create the amorphous forms of the instant invention. The instant invention comprises all amorphous forms of the compounds of formula I and their pharmaceutically acceptable salts.

The compounds of formula I may exist in different tautomeric forms. One skilled in the art will recognize that amidines, amides, guanidines, ureas, thioureas, heterocycles and the like can exist in tautomeric forms. All possible tautomeric forms of the amidines, amides, guanidines, ureas, thioureas, heterocycles and the like of all of the embodiments of formula I-IV are within the scope of the instant invention.

"Enantiomers" refer to two stereoisomers of a compound which are non-superimposable mirror images of one another.

Stereochemical definitions and conventions used herein generally follow S. P. Parker, Ed., *McGraw-Hill Dictionary of Chemical Terms* (1984) McGraw-Hill Book Company, New York; and Eliel, E. and Wilen, S., *Stereochemistry of Organic Compounds* (1994) John Wiley & Sons, Inc., New York. Many organic compounds exist in optically active forms, i.e., they have the ability to rotate the plane of plane-polarized light. In describing an optically active compound, the prefixes D and L or R and S are used to denote the absolute configuration of the molecule about its chiral center(s). The prefixes d and l, D and L, or (+) and (-) are employed to designate the sign of rotation of plane-polarized light by the compound, with S, (-), or l meaning that the compound is levorotatory while a compound prefixed with R, (+), or d is dextrorotatory. For a given chemical structure, these stereoisomers are identical except that they are mirror images of one another. A specific stereoisomer may also be referred to as an enantiomer, and a mixture of such isomers is often called an enantiomeric mixture. A 50:50 mixture of enantiomers is referred to as a racemic mixture or a racemate, which may occur where there has been no stereoselection or stereospecificity in a chemical reaction or process. The terms "racemic mixture" and "racemate" refer to an equimolar mixture of two enantiomeric species, devoid of optical activity.

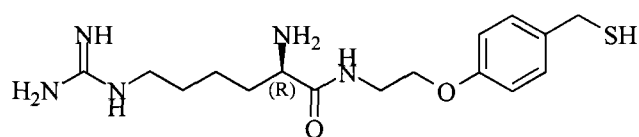
A single stereoisomer, e.g. an enantiomer, substantially free of its stereoisomer may be obtained by resolution of the racemic mixture using a method such as formation of diastereomers using optically active resolving agents ("Stereochemistry of Carbon Compounds," (1962) by E. L. Eliel, McGraw Hill; Lochmuller, C. H., (1975) *J. Chromatogr.*, 113:(3) 283-302). Racemic mixtures of chiral compounds of the invention can be separated

and isolated by any suitable method, including: (1) formation of ionic, diastereomeric salts with chiral compounds and separation by fractional crystallization or other methods, (2) formation of diastereomeric compounds with chiral derivatizing reagents, separation of the diastereomers, and conversion to the pure stereoisomers, and (3) separation of the substantially pure or enriched stereoisomers directly under chiral conditions.

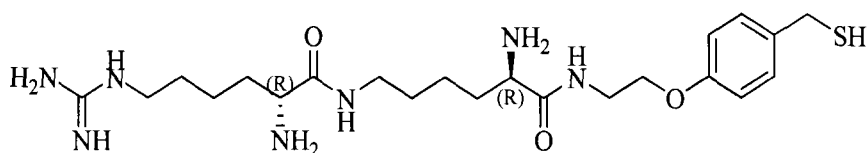
"Diastereomer" refers to a stereoisomer with two or more centers of chirality and whose molecules are not mirror images of one another. Diastereomers have different physical properties, e.g. melting points, boiling points, spectral properties, and reactivities. Mixtures of diastereomers may separate under high resolution analytical procedures such as electrophoresis and chromatography.

As discussed above, the compounds used to prepare the compositions of the present invention may be in the form of a pharmaceutically acceptable free base. Because the free base of the compound is generally less soluble in aqueous solutions than the salt, free base compositions are employed to provide more sustained release of active agent to the lungs. An active agent present in the lungs in particulate form which has not dissolved into solution is not available to induce a physiological response, but serves as a depot of bioavailable drug which gradually dissolves into solution.

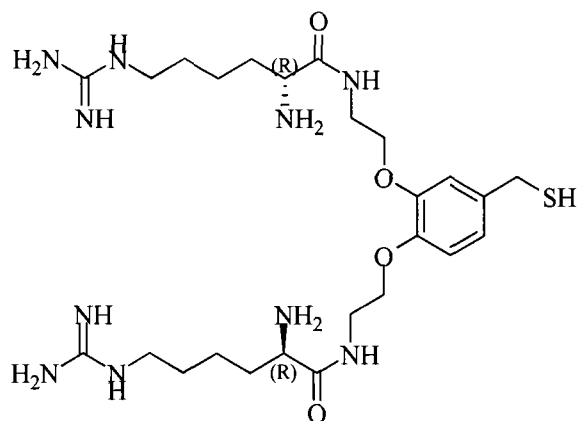
In a preferred embodiment, the compound of formula (I) is



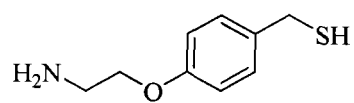
In another preferred embodiment, the compound of formula (I) is



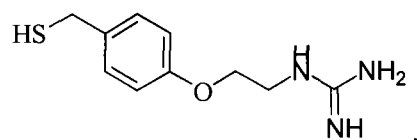
In another preferred embodiment, the compound of formula (I) is



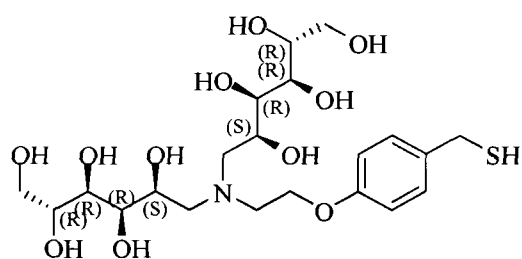
In another preferred embodiment, the compound of formula (I) is



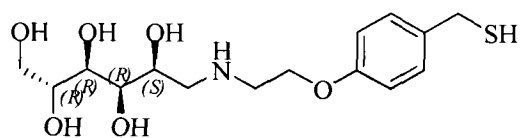
In another preferred embodiment, the compound of formula (I) is



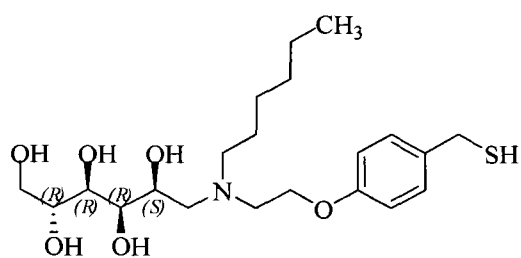
In another preferred embodiment, the compound of formula (I) is



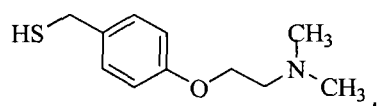
In another preferred embodiment, the compound of formula (I) is



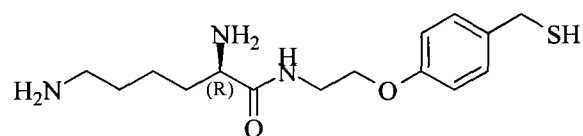
In another preferred embodiment, the compound of formula (I) is



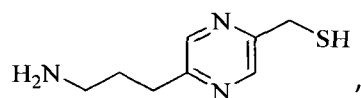
In another preferred embodiment, the compound of formula (I) is



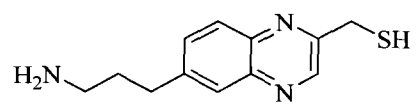
In another preferred embodiment, the compound of formula (I) is



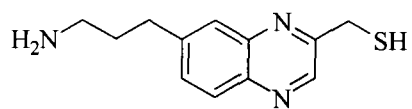
In another preferred embodiment, the compound of formula (I) is



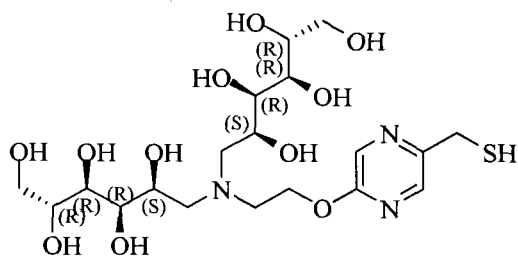
In another preferred embodiment, the compound of formula (I) is



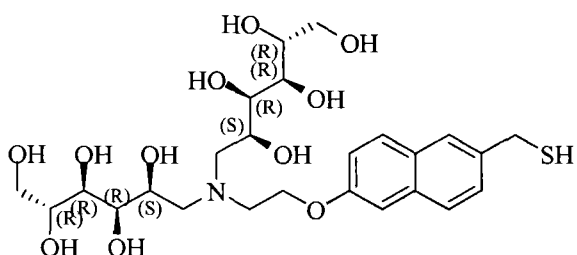
In another preferred embodiment, the compound of formula (I) is



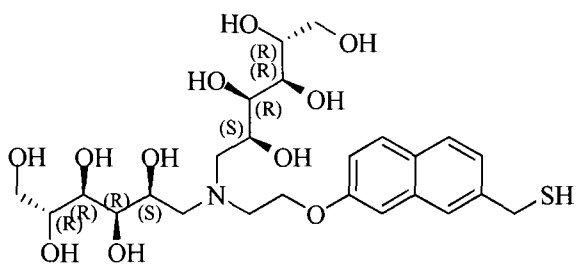
In another preferred embodiment, the compound of formula (I) is



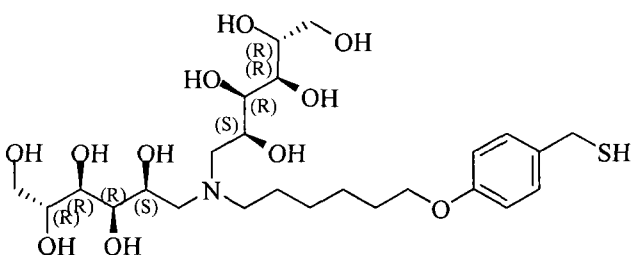
In another preferred embodiment, the compound of formula (I) is



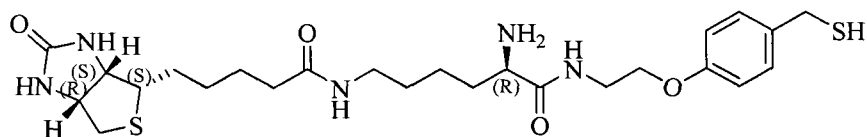
In another preferred embodiment, the compound of formula (I) is



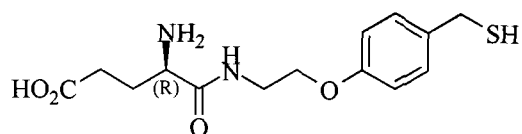
In another preferred embodiment, the compound of formula (I) is



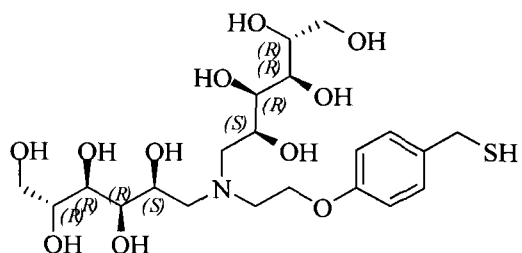
In another preferred embodiment, the compound of formula (I) is



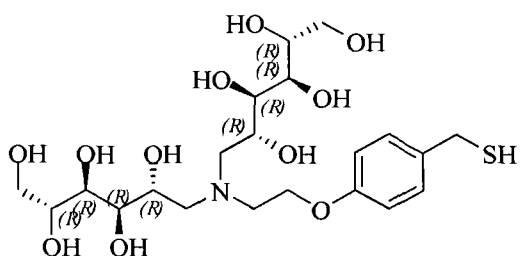
In another preferred embodiment, the compound of formula (I) is



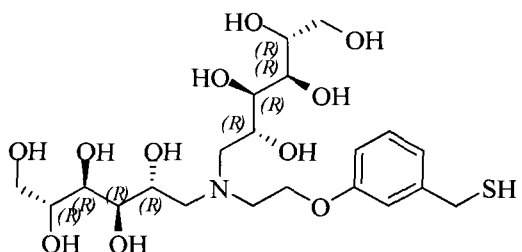
In a particularly preferred embodiment, the compound of formula (I) is



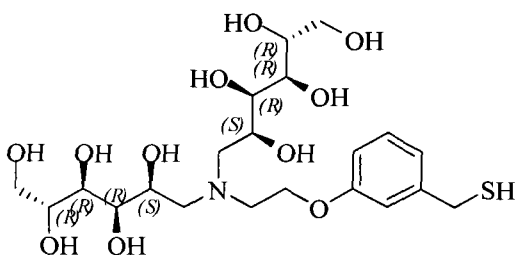
In another particularly preferred embodiment, the compound of formula (I) is



In another particularly preferred embodiment, the compound of formula (I) is



In another particularly preferred embodiment, the compound of formula (I) is



Prodrugs of Monothiol Mucolytics:

Many modern drugs are discovered through high-throughput screening or combinatorial chemistry. These compounds often are selected for their high pharmacological efficacy but unintentionally have poor drug-like characteristics (*e.g.*, solubility, bioavailability, stability). One strategy to overcome these physiochemical, biopharmaceutical, and pharmacokinetic limitations is to use a prodrug form of the compound, a molecule that is

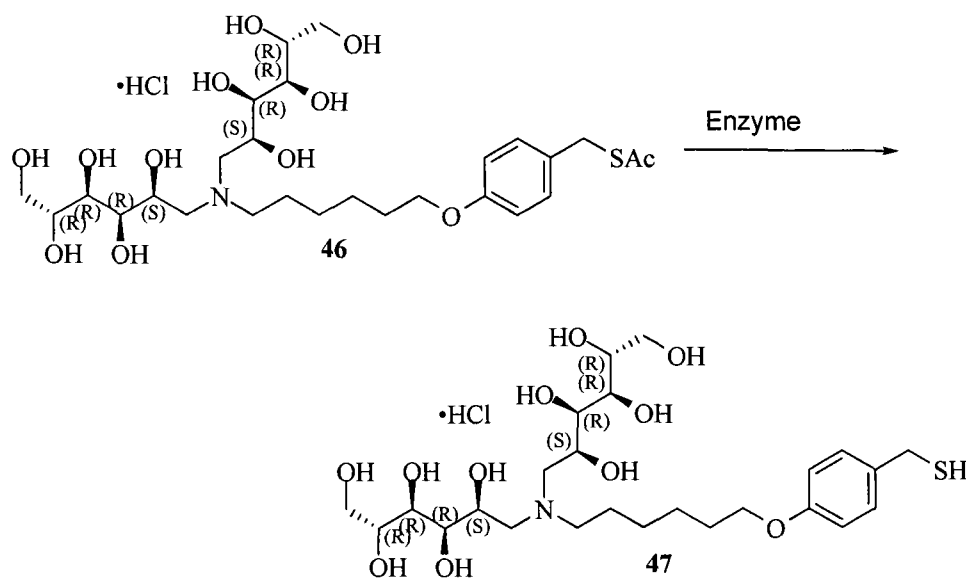
inactive until undergoing an enzymatic or chemical transformation *in vivo*. Depending on the type of modification, prodrugs can have key advantages over their active counterparts: (1) increased stability and shelf-life, (2) increased aqueous solubility, (3) improved bioavailability, (4) increased lipophilicity/permeability, and (5) improved parenteral administration.

Of the drugs approved worldwide, 5-7% can be classified as prodrugs. These drugs are classified into two categories, bioprecursor prodrugs or carrier-linked prodrugs. Bioprecursor prodrugs are converted into pharmacologically active drugs by metabolic or chemical transformation. Carrier-linked prodrugs have a promoiety that is covalently linked to an active parent molecule. This promoiety is released, usually by enzymatic hydrolysis, activating the parent molecule once delivered to the therapeutic location. Design of the prodrug moiety is usually based on the drug-like characteristics that need improvement in a particular molecule, the available functional groups that are amenable to a promoiety, and the targeted organ or tissue. In cases where the promoiety cannot be directly attached due to reasons such as steric hinderance, spacers or linkers are also added. In order to be well-tolerated, the promoiety should be non-immunogenic, stable until reaching the therapeutic tissue, and rapidly excreted from the body, once cleaved from the parent. Esters are one of the most commonly used promoieties, due to their ease of removal from the parent drug by ubiquitous esterases (*e.g.*, acetylcholinesterases, butyrylcholinesterases, carboxylesterases, arlesterases), capability of increasing drug solubility by masking charge groups, such as carboxylic acids and phophates, and relatively simple synthesis. Some other common functional groups that are utilized as promoieties are: carbonates, carbamates, amides, phosphates, and oximes.

Prodrugs could be particularly useful as inhaled therapeutics for muco-obstructive respiratory diseases, such as chronic bronchitis (CB), including the most common lethal genetic form of chronic bronchitis, cystic fibrosis (CF). We also hypothesized that additional molecular features can improve tolerability and duration of action of the monothiol mucolytics.

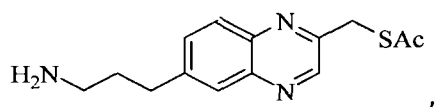
Specifically, we developed mucolytic pro-drugs, by integrating enzymatically labile, thiol-capping groups. These pro-drug mucolytic agents are advantageous in that: 1) they are completely inactive, and therefore, protected from auto-oxidation in solution; 2) the thiol protecting groups render the compounds completely odorless; and 3) the molecules can be designed to alter the rate of activation *in vivo* and can, therefore, be used to slow compound activation and to extend the duration of pharmacological action.

The present invention provides a series of mucolytic pro-drugs (see $R^6 =$ other than H) that are activated by common enzymes that are present in the extracellular milieu (*e.g.*, nucleotidases, phosphatases, and esterases). As a proof-of-concept, the reducing kinetics of the pro-drug compound **46** in the presence or absence of an activating esterase were tested. Under the conditions tested, **46** alone does not reduce disulfide

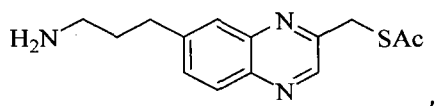


bonds, whereas the parent molecule **47** fully reduces all available disulfides in <10 seconds. However, the addition of an enzyme, capable of enzymatically activating **46**, produces a concentration dependent increase in reaction rates. Importantly, **P-46** and **47** both reduce MUC5B in human mucus samples, with kinetics similar to what is predicted above, demonstrating that enzymatic activities required for activation are present in mucus (Figures 8 and 9).

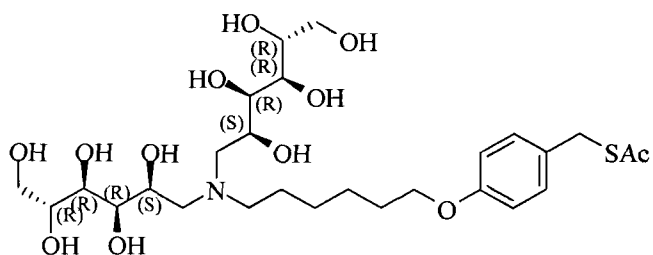
As discussed above, the compounds used to prepare the compositions of the present invention may be in the form of a pharmaceutically acceptable free base or acid addition salt. In preferred embodiment, the prodrug compound of formula (I) is



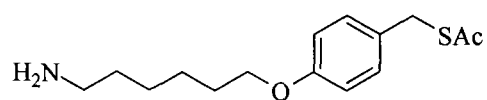
In another preferred embodiment, the prodrug compound of formula (I) is



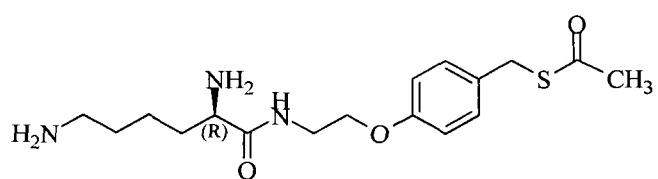
In another preferred embodiment, the prodrug compound of formula (I) is



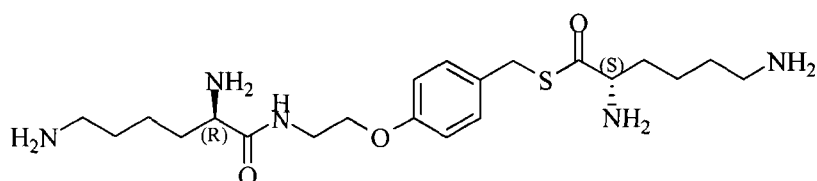
In another preferred embodiment, the prodrug compound of formula (I) is



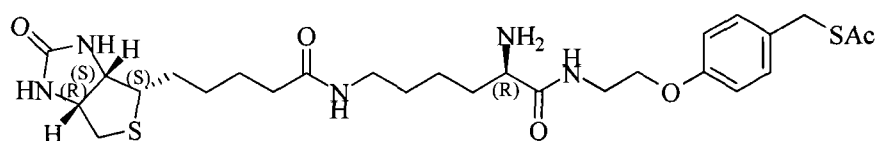
In another preferred embodiment, the prodrug compound of formula (I) is



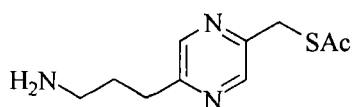
In another preferred embodiment, the prodrug compound of formula (I) is



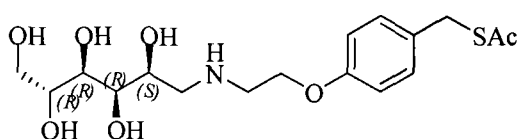
In another preferred embodiment, the prodrug compound of formula (I) is



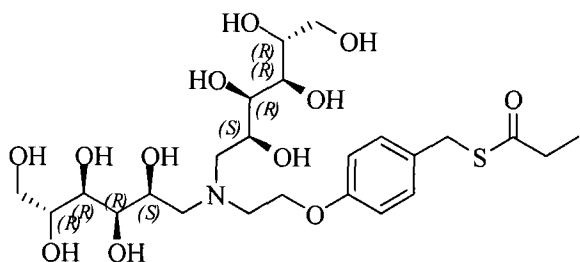
In another preferred embodiment, the prodrug compound of formula (I) is



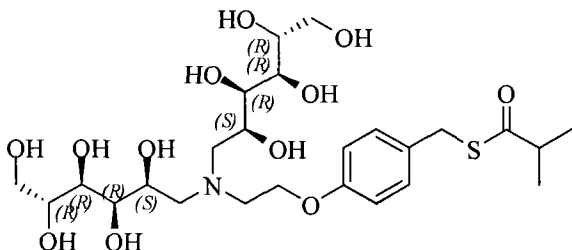
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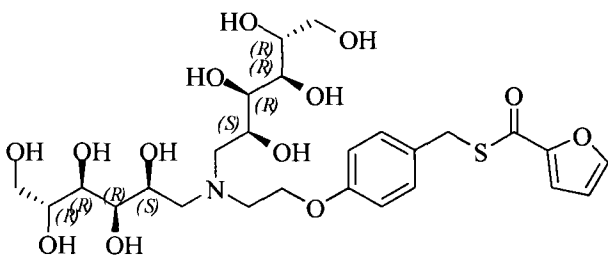
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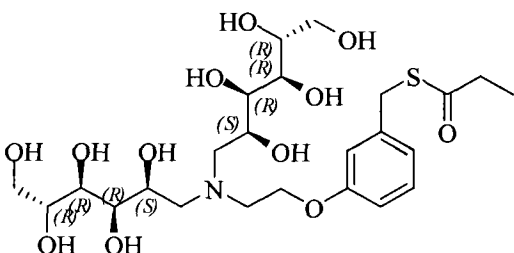
In another preferred embodiment, the prodrug compound of formula (I) is



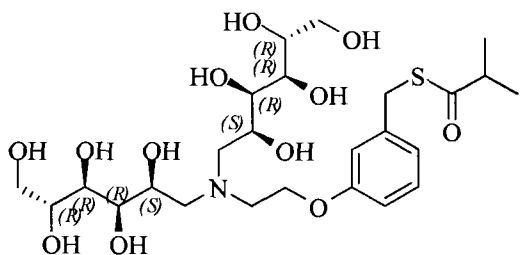
In another preferred embodiment, the prodrug compound of formula (I) is



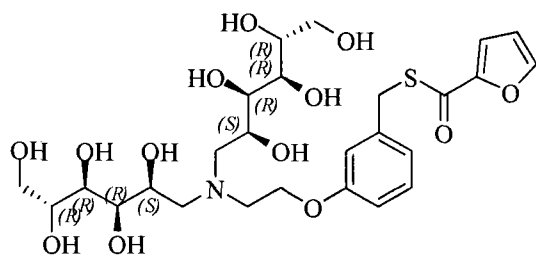
In another preferred embodiment, the prodrug compound of formula (I) is



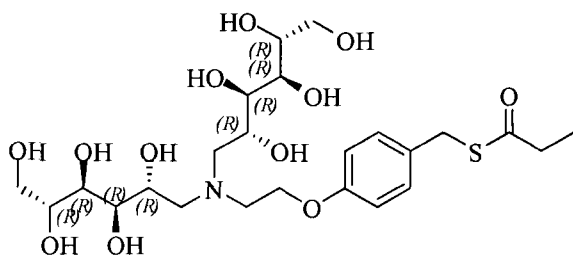
In another preferred embodiment, the prodrug compound of formula (I) is



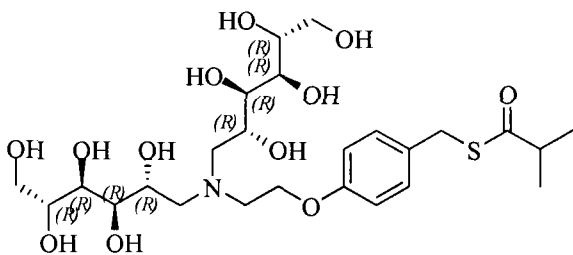
In another preferred embodiment, the prodrug compound of formula (I) is



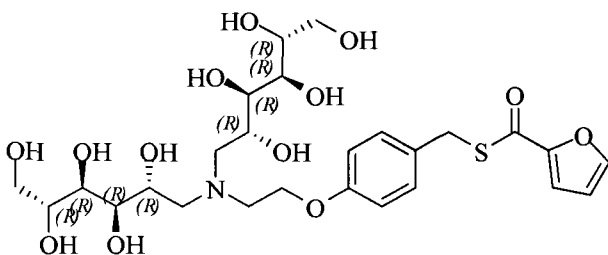
In another preferred embodiment, the prodrug compound of formula (I) is



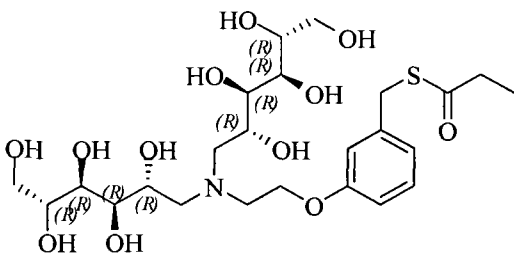
In another preferred embodiment, the prodrug compound of formula (I) is



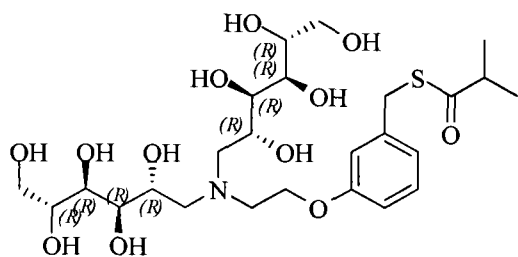
In another preferred embodiment, the prodrug compound of formula (I) is



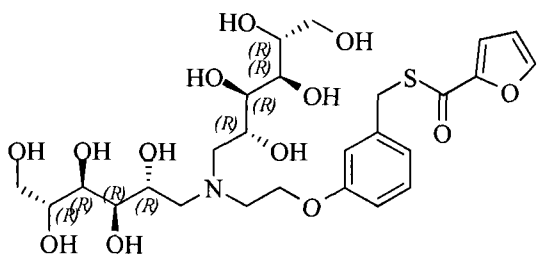
In another preferred embodiment, the prodrug compound of formula (I) is



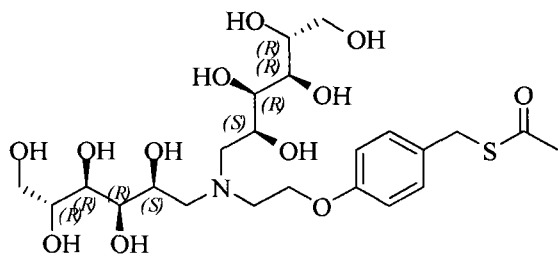
In another preferred embodiment, the prodrug compound of formula (I) is



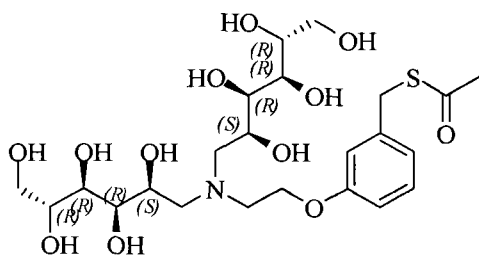
In another preferred embodiment, the prodrug compound of formula (I) is



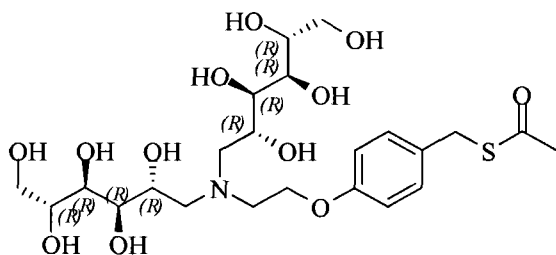
In a particularly preferred embodiment, the prodrug compound of formula (I) is



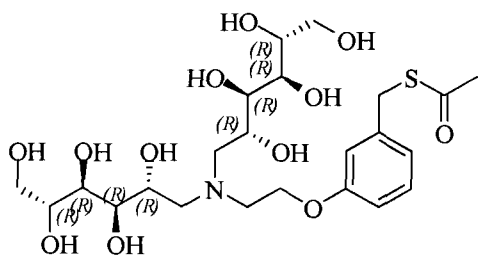
In another particularly preferred embodiment, the prodrug compound of formula (I) is



In another particularly preferred embodiment, the prodrug compound of formula (I) is



In another particularly preferred embodiment, the prodrug compound of formula (I) is



The present invention also provides methods of treatment that take advantage of the properties of the compounds described herein as discussed above. Thus, subjects that may be treated by the methods of the present invention include, but are not limited to, patients afflicted with cystic fibrosis, pulmonary fibrosis, asthma, primary ciliary dyskinesia, chronic bronchitis, bronchiectasis chronic obstructive airway disease, artificially ventilated patients, patients with acute pneumonia, etc. The present invention may be used to obtain a sputum sample from a patient by administering the active compounds to at least one lung of a patient, and then inducing or collecting a sputum sample from that patient. Typically, the invention will be administered to respiratory mucosal surfaces via liquid aerosols, dry powders, or lavage.

Subjects that may be treated by the method of the present invention also include patients being administered supplemental oxygen nasally (a regimen that tends to dry the airway surfaces); patients afflicted with an allergic disease or response (e.g., an allergic response to pollen, dust, animal hair or particles, insects or insect particles, etc.) that affects nasal airway surfaces; patients afflicted with a bacterial infection e.g., staphylococcus infections such as *Staphylococcus aureus* infections, *Hemophilus influenza* infections, *Streptococcus pneumoniae* infections, *Pseudomonas aeruginosa* infections, etc.) of the nasal airway surfaces; patients afflicted with an inflammatory disease that affects nasal airway surfaces; or patients afflicted with sinusitis (wherein the active agent or agents are administered to promote drainage of congested mucous secretions in the sinuses by administering an amount effective to promote drainage of congested fluid in the sinuses), or combined, Rhinosinusitis. The invention may be administered to rhino-sinal surfaces by topical delivery, including aerosols and drops.

The present invention may be use to improve fibrosing idiopathic interstitial pneumonias (fIIPs), lung diseases characterized by progressive scarring of the alveolar interstitium that lead to significant morbidity and mortality. Idiopathic pulmonary fibrosis (IPF) is the most common and most severe form of fIIP with a median survival of 3 years, affects 50,000 individuals annually in the U.S., and will increase in prevalence as our

population ages (G. Raghu, D. Weycker, J. Edelsberg, W. Z. Bradford, G. Oster, Incidence and prevalence of idiopathic pulmonary fibrosis. *Am J Respir Crit Care Med* 174, 810 (Oct 1, 2006). Importantly, most previously attempted therapies have been targeted at the fibroproliferative matrix in IPF, but these have proven ineffective. Rare mutations have been associated with IPF, however, these variants account for a small proportion of the attributable risk. A recent discovery that MUC5B is a highly significant and common genetic risk factor for established IPF (M. A. Seibold et al., A common MUC5B promoter polymorphism and pulmonary fibrosis. *N Engl J Med* 364, 1503 (Apr 21, 2011).) suggests that the MUC5B variant has the potential to detect preclinical or mild disease. Thus, the present invention may be used to treat an underlying defect in MUC5B in pulmonary fibrosis.

The present invention may be used to improve mucus clearance other than airway surfaces. Such other mucosal surfaces include gastrointestinal surfaces, oral surfaces, genitourethral surfaces, and ocular surfaces or surfaces of the eye. For example, the active compounds of the present invention may be administered by any suitable means, including locally/topically, orally, or rectally, in an effective amount.

In another aspect, a post-exposure prophylactic treatment or therapeutic treatment method is provided for treating infection from an airborne pathogen comprising administering an effective amount of the compounds of formula (I-VII) to the lungs of an individual in need of such treatment against infection from an airborne pathogen. The pathogens which may be protected against by the prophylactic post exposure, rescue and therapeutic treatment methods of the invention include any pathogens which may enter the body through the mouth, nose or nasal airways, thus proceeding into the lungs. Typically, the pathogens will be airborne pathogens, either naturally occurring or by aerosolization. The pathogens may be naturally occurring or may have been introduced into the environment intentionally after aerosolization or other method of introducing the pathogens into the environment. Many pathogens which are not naturally transmitted in the air have been or may be aerosolized for use in bioterrorism. The pathogens for which the treatment of the invention may be useful includes, but is not limited to, category A, B and C priority pathogens as set forth by the NIAID. These categories correspond generally to the lists compiled by the Centers for Disease Control and Prevention (CDC). As set up by the CDC, Category A agents are those that can be easily disseminated or transmitted person-to-person, cause high mortality, with potential for major public health impact. Category B agents are next in priority and include those that are moderately easy to disseminate and cause moderate morbidity and low mortality. Category C consists of emerging pathogens that could be

engineered for mass dissemination in the future because of their availability, ease of production and dissemination and potential for high morbidity and mortality. Particular examples of these pathogens are anthrax and plague. Additional pathogens which may be protected against or the infection risk therefrom reduced include influenza viruses, rhinoviruses, adenoviruses and respiratory syncytial viruses, and the like. A further pathogen which may be protected against is the coronavirus which is believed to cause severe acute respiratory syndrome (SARS).

The present invention also relates to the use of mucolytic agents of Formula I, or a pharmaceutically acceptable salt thereof, for preventing, mitigating, and/or treating deterministic health effects to the respiratory tract caused by exposure to radiological materials, particularly respirable aerosols containing radionuclides from nuclear attacks, such as detonation of radiological dispersal devices (RDD), or accidents, such as nuclear power plant disasters. As such, provided herein is a method for preventing, mitigating, and/or treating deterministic health effects to the respiratory tract and/or other bodily organs caused by respirable aerosols containing radionuclides in a recipient in need thereof, including in a human in need thereof, said method comprising administering to said human an effective amount of a compound of Formula (I), or a pharmaceutically acceptable salt thereof.

A major concern associated with consequence management planning for exposures of members of the public to respirable aerosols containing radionuclides from nuclear attacks, such as detonation of radiological dispersal devices (RDD), or accidents, such as nuclear power plant disasters is how to prevent, mitigate or treat potential deterministic health effects to the respiratory tract, primarily the lung. It is necessary to have drugs, techniques and procedures, and trained personnel prepared to manage and treat such highly internally contaminated individuals.

Research has been conducted to determine ways in which to prevent, mitigate or treat potential damage to the respiratory tract and various organs in the body that is caused by internally deposited radionuclides. To date, most of the research attention has focused on strategies designed to mitigate health effects from internally deposited radionuclides by accelerating their excretion or removal. These strategies have focused on soluble chemical forms that are capable of reaching the blood stream and are deposited at remote systemic sites specific to a given radioelement. Such approaches will not work in cases where the deposited radionuclide is in relatively insoluble form. Studies have shown that many, if not most of the physicochemical forms of dispersed radionuclides from RDDs, will be in relatively insoluble form.

The only method known to effectively reduce the radiation dose to the lungs from inhaled insoluble radioactive aerosols is bronchoalveolar lavage or BAL. This technique, which was adapted from that already in use for the treatment of patients with alveolar proteinosis, has been shown to be a safe, repeatable procedure, even when performed over an extended period of time. Although there are variations in procedure, the basic method for BAL is to anaesthetize the subject, followed by the slow introduction of isotonic saline into a single lobe of the lung until the function residual capacity is reached. Additional volumes are then added and drained by gravity.

The results of studies using BAL on animals indicate that about 40% of the deep lung content can be removed by a reasonable sequence of BALs. In some studies, there was considerable variability among animals in the amount of radionuclide recovered. The reasons for the variability are currently not understood.

Further, based on a study on animals, it is believed that a significant dose reduction from BAL therapy results in mitigation of health effects due to inhalation of insoluble radionuclides. In the study, adult dogs inhaled insoluble ^{144}Ce -FAP particles. Two groups of dogs were given lung contents of ^{144}Ce known to cause radiation pneumonitis and pulmonary fibrosis (about 2 MBq/kg body mass), with one group being treated with 10 unilateral lavages between 2 and 56 days after exposure, the other untreated. A third group was exposed at a level of ^{144}Ce comparable to that seen in the BAL-treated group after treatment (about 1 MBq/kg), but these animals were untreated. All animals were allowed to live their lifespans, which extended to 16 years. Because there is variability in initial lung content of ^{144}Ce among the dogs in each group, the dose rates and cumulative doses for each group overlap. Nevertheless, the effect of BAL in reducing the risk from pneumonitis/fibrosis was evident from the survival curves. In the untreated dogs with lung contents of 1.5-2.5 MBq/kg, the mean survival time was 370 ± 65 d. For the treated dogs, the mean survival was 1270 ± 240 d, which was statistically significantly different. The third group, which received lung contents of ^{144}Ce of 0.6-1.4 MBq had a mean survival time of 1800 ± 230 , which was not statistically different from the treated group. Equally important to the increased survival, the dogs in the high-dose untreated group died from deterministic effects to lung (pneumonitis/fibrosis) while the treated dogs did not. Instead, the treated dogs, like the dogs in the low-dose untreated group, mostly had lung tumors (hemangiosarcoma or carcinoma). Therefore, the reduction in dose resulting from BAL treatment appears to have produced biological effects in lung that were predictable based on the radiation doses that the lungs received.

Based on these results, it is believed that decreasing the residual radiological dose further by any method or combination of methods for enhancing the clearance of particles from the lung would further decrease the probability of health effects to lung. However, BAL is a procedure that has many drawbacks. BAL is a highly invasive procedure that must be performed at specialized medical centers by trained pulmonologists. As such, a BAL procedure is expensive. Given the drawbacks of BAL, it is not a treatment option that would be readily and immediately available to persons in need of accelerated removal of radioactive particles, for example, in the event of a nuclear attack. In the event of a nuclear attack or a nuclear accident, immediate and relatively easily administered treatment for persons who have been exposed or who are at risk of being exposed is needed. Sodium channel blockers administered as an inhalation aerosol have been shown to restore hydration of airway surfaces. Such hydration of airway surfaces aids in clearing accumulated mucus secretions and associated particulate matter from the lung. As such, without being bound by any particular theory, it is believed that sodium channel blockers can be used in combination with mucolytic agents described in their invention to accelerate the removal of radioactive particles from airway passages.

As discussed above, the greatest risk to the lungs following a radiological attack, such as a dirty bomb, results from the inhalation and retention of insoluble radioactive particles. As a result of radioactive particle retention, the cumulative exposure to the lung is significantly increased, ultimately resulting in pulmonary fibrosis/pneumonitis and potentially death. Insoluble particles cannot be systemically cleared by chelating agents because these particles are not in solution. To date, the physical removal of particulate matter through BAL is the only therapeutic regimen shown to be effective at mitigating radiation-induced lung disease. As discussed above, BAL is not a realistic treatment solution for reducing the effects of radioactive particles that have been inhaled into the body. As such, it is desirable to provide a therapeutic regimen that effectively aids in clearing radioactive particles from airway passages and that, unlike BAL, is relatively simple to administer and scalable in a large-scale radiation exposure scenario. In addition, it is also desirable that the therapeutic regimen be readily available to a number of people in a relatively short period of time.

In an aspect of the present invention, a method for preventing, mitigating, and/or treating deterministic health effects to the respiratory tract and/or other bodily organs caused by respirable aerosols containing radionuclides comprises administering an effective amount of a mucolytic agent of Formula I or a pharmaceutically acceptable salt thereof to an

individual in need. In a feature of this aspect, the mucolytic agent is administered in conjunction with an osmolyte. With further regard to this feature, the osmolyte is hypertonic saline. In a further feature, the mucolytic agent and the osmolyte are administered in conjunction with an ion transport modulator. With further regard to this feature, the ion transport modulator may be selected from the group consisting of β -agonists, CFTR potentiators, purinergic receptor agonists, lubiprostones, and protease inhibitors. In another feature of this aspect, the radionuclides are selected from the group consisting of Cobalt-60, Cesium-137, Iridium-192, Radium-226, Phosphorus-32, Strontium-89 and 90, Iodine-125, Thallium-201, Lead-210, Thorium-234, Uranium-238, Plutonium, Cobalt-58, Chromium-51, Americium, and Curium. In a further feature, the radionuclides are from a radioactive disposal device. In yet another feature, the mucolytic agent or pharmaceutically acceptable salt thereof is administered in an aerosol suspension of respirable particles which the individual inhales. In an additional feature, the mucolytic agent or a pharmaceutically acceptable salt thereof is administered post-exposure to the radionuclides.

The present invention is concerned primarily with the treatment of human subjects, but may also be employed for the treatment of other mammalian subjects, such as dogs and cats, for veterinary purposes.

Another aspect of the present invention is a pharmaceutical composition, comprising a compound of formula I in a pharmaceutically acceptable carrier (e.g., an aqueous carrier solution). In general, the compound of formula I is included in the composition in an amount effective to reduce the viscosity of mucus on mucosal surfaces.

MUCOLYTIC COMBINATION THERAPIES:

An aspect of the present invention is the COMBINATION of mucolytic agents with other drugs or excipients to improve the efficacy and tolerability of the compounds described in this invention.

In one embodiment of this invention, mucolytic agents are utilized to provide access to other therapeutic agents through the mucus layer to the airway epithelium. Mucus forms a diffusion barrier which can prevent therapeutic molecules from reaching their intended site of action.

The access of the following therapeutic agents to their site of action in the airway epithelium could be enhanced by the pre- or co-treatment with the mucolytic agents described in this invention.

In one embodiment of this invention, mucolytic agents are utilized in combination with other therapies or small molecule drugs to provide an advantageous additive or synergistic benefit.

Mucolytic Combinations with Osmotically Active Agents:

Another aspect of the present invention is administering reducing agents in combination with osmolytes. A simple means to restore airway surface hydration in subjects with muco-obstructive diseases is to inhale hypertonic osmolyte solutions (most frequently 7% hypertonic saline (HS)), which draws water onto the airway surface. Rehydration of the lubricant periciliary layer (PCL) of the airway surface facilitates mucus clearance and, therefore, the removal of inhaled infectious agents. Mucus rehydration achieved by the administration of hypertonic solutions and disruption of mucus polymers by reducing agents is expected to produce a synergistic reduction in mucus viscosity and elasticity, improving the transportability and clearance of mucus.

Inhaled HS is a unique therapeutic agent as it is used by ~60% of CF patients nationwide, but is not FDA approved for daily use for pulmonary disease. As such, HS has not undergone the rigorous clinical testing to identify the dose and dosing frequency that are most efficacious and well tolerated. Instead, the HS regime has been optimized in practice by patients and physicians. Most commonly, HS is administered as two 15 minute inhalation treatments of 4 mL of 7% hypertonic saline per treatment. The tonicity of HS used by patients (7% NaCl) has been identified as a maximum concentration that is generally tolerated (i.e. minimal irritation or bronchoconstriction).

The compounds of Formula I may also be used in conjunction with osmolytes thus lowering the dose of the compound needed to hydrate mucosal surfaces. This important property means that the compound will have a lower tendency to cause undesired side-effects. Active osmolytes of the present invention are molecules or compounds that are osmotically active (*i.e.*, are "osmolytes"). "Osmotically active" compounds of the present invention are membrane-impermeable (*i.e.*, essentially non-absorbable) on the airway or pulmonary epithelial surface. The terms "airway surface" and "pulmonary surface," as used herein, include pulmonary airway surfaces such as the bronchi and bronchioles, alveolar surfaces, and nasal and sinus surfaces. Active compounds of the present invention may be ionic osmolytes (*i.e.*, salts), or may be non-ionic osmolytes (*i.e.*, sugars, sugar alcohols, and organic osmolytes). It is specifically intended that both racemic forms of the active compounds that are racemic in nature are included in the group of active compounds that are useful in the present invention. It is to be noted that all racemates, enantiomers,

diastereomers, tautomers, polymorphs and pseudopolymorphs and racemic mixtures of the osmotically active compounds are embraced by the present invention.

Active compounds of the present invention may be ionic osmolytes (i.e., salts), or may be non-ionic osmolytes (i.e., sugars, sugar alcohols, and organic osmolytes). It is specifically intended that both racemic forms of the active compounds that are racemic in nature are included in the group of active compounds that are useful in the present invention. It is to be noted that all racemates, enantiomers, diastereomers, tautomers, polymorphs and pseudopolymorphs and racemic mixtures of the osmotically active compounds are embraced by the present invention.

Active osmolytes useful in the present invention that are ionic osmolytes include any salt

of a pharmaceutically acceptable anion and a pharmaceutically acceptable cation. Preferably, either (or both) of the anion and cation are non-absorbable (i.e., osmotically active and not subject to rapid active transport) in relation to the airway surfaces to which they are administered. Such compounds include but are not limited to anions and cations that are contained in FDA approved commercially marketed salts, see, e.g., Remington: The Science and Practice of Pharmacy, Vol. II, pg. 1457 (19^{sup}.th Ed. 1995), incorporated herein by reference, and can be used in any combination including their conventional combinations.

Pharmaceutically acceptable osmotically active anions that can be used to carry out the present invention include, but are not limited to, acetate, benzenesulfonate, benzoate, bicarbonate, bitartrate, bromide, calcium edetate, camsylate (camphorsulfonate), carbonate, chloride, citrate, dihydrochloride, edetate, edisylate (1,2-ethanedisulfonate), estolate (lauryl sulfate), esylate (1,2-ethanedisulfonate), fumarate, gluceptate, gluconate, glutamate, glycollylarsanilate (p-glycollamidophenylarsonate), hexylresorcinate, hydrabamine (N,N'-Di(dehydroabietyl)ethylenediamine), hydrobromide, hydrochloride, hydroxynaphthoate, iodide, isethionate, lactate, lactobionate, malate, maleate, mandelate, mesylate, methylbromide, methylnitrate, methylsulfate, mucate, napsylate, nitrate, nitrite, pamoate (embonate), pantothenate, phosphate or diphosphate, polygalacturonate, salicylate, stearate, subacetate, succinate, sulfate, tannate, tartrate, teoclate (8-chlorotheophyllinate), triethiodide, bicarbonate, etc. Particularly preferred anions include chloride sulfate, nitrate, gluconate, iodide, bicarbonate, bromide, and phosphate.

Pharmaceutically acceptable cations that can be used to carry out the present invention include, but are not limited to, organic cations such as benzathine (N,N'-dibenzylethylenediamine), chlorprocaine, choline, diethanolamine, ethylenediamine,

meglumine (N-methyl D-glucamine), procaine, D-lysine, L-lysine, D-arginine, L-arginine, triethylammonium, N-methyl D-glycerol, and the like. Particularly preferred organic cations are 3-carbon, 4-carbon, 5-carbon and 6-carbon organic cations. Metallic cations useful in the practice of the present invention include but are not limited to aluminum, calcium, lithium, magnesium, potassium, sodium, zinc, iron, ammonium, and the like. Particularly preferred cations include sodium, potassium, choline, lithium, meglumine, D-lysine, ammonium, magnesium, and calcium.

Specific examples of osmotically active salts that may be used with the sodium channel blockers described herein to carry out the present invention include, but are not limited to, sodium chloride, potassium chloride, choline chloride, choline iodide, lithium chloride, meglumine chloride, L-lysine chloride, D-lysine chloride, ammonium chloride, potassium sulfate, potassium nitrate, potassium gluconate, potassium iodide, ferric chloride, ferrous chloride, potassium bromide, etc. Either a single salt or a combination of different osmotically active salts may be used to carry out the present invention. Combinations of different salts are preferred. When different salts are used, one of the anion or cation may be the same among the differing salts.

Osmotically active compounds of the present invention also include non-ionic osmolytes such as sugars, sugar-alcohols, and organic osmolytes. Sugars and sugar-alcohols useful in the practice of the present invention include but are not limited to 3-carbon sugars (e.g., glycerol, dihydroxyacetone); 4-carbon sugars (e.g., both the D and L forms of erythrose, threose, and erythrulose); 5-carbon sugars (e.g., both the D and L forms of ribose, arabinose, xylose, lyxose, psicose, fructose, sorbose, and tagatose); and 6-carbon sugars (e.g., both the D and L forms of altose, allose, glucose, mannose, gulose, idose, galactose, and talose, and the D and L forms of allo-heptulose, allo-hepulose, gluco-heptulose, manno-heptulose, gulo-heptulose, ido-heptulose, galacto-heptulose, talo-heptulose). Additional sugars useful in the practice of the present invention include raffinose, raffinose series oligosaccharides, and stachyose. Both the D and L forms of the reduced form of each sugar/sugar alcohol useful in the present invention are also active compounds within the scope of the invention. For example, glucose, when reduced, becomes sorbitol; within the scope of the invention, sorbitol and other reduced forms of sugar/sugar alcohols (e.g., mannitol, dulcitol, arabitol) are accordingly active compounds of the present invention.

Osmotically active compounds of the present invention additionally include the family of non-ionic osmolytes termed "organic osmolytes." The term "organic osmolytes" is generally used to refer to molecules used to control intracellular osmolality in the kidney. See

e.g., J. S. Handler et al., *Comp. Biochem. Physiol.*, 117, 301-306 (1997); M. Burg, *Am. J. Physiol.* 268, F983-F996 (1995), each incorporated herein by reference. Although the inventor does not wish to be bound to any particular theory of the invention, it appears that these organic osmolytes are useful in controlling extracellular volume on the airway/pulmonary surface. Organic osmolytes useful as active compounds in the present invention include but are not limited to three major classes of compounds: polyols (polyhydric alcohols), methylamines, and amino acids. The polyol organic osmolytes considered useful in the practice of this invention include, but are not limited to, inositol, myo-inositol, and sorbitol. The methylamine organic osmolytes useful in the practice of the invention include, but are not limited to, choline, betaine, carnitine (L-, D- and DL forms), phosphorylcholine, lyso-phosphorylcholine, glycerophosphorylcholine, creatine, and creatine phosphate. The amino acid organic osmolytes of the invention include, but are not limited to, the D- and L-forms of glycine, alanine, glutamine, glutamate, aspartate, proline and taurine. Additional osmolytes useful in the practice of the invention include tihulose and sarcosine. Mammalian organic osmolytes are preferred, with human organic osmolytes being most preferred. However, certain organic osmolytes are of bacterial, yeast, and marine animal origin, and these compounds are also useful active compounds within the scope of the present invention.

Under certain circumstances, an osmolyte precursor may be administered to the subject; accordingly, these compounds are also useful in the practice of the invention. The term "osmolyte precursor" as used herein refers to a compound which is converted into an osmolyte by a metabolic step, either catabolic or anabolic. The osmolyte precursors of this invention include, but are not limited to, glucose, glucose polymers, glycerol, choline, phosphatidylcholine, lyso-phosphatidylcholine and inorganic phosphates, which are precursors of polyols and methylamines. Precursors of amino acid osmolytes within the scope of this invention include proteins, peptides, and polyamino acids, which are hydrolyzed to yield osmolyte amino acids, and metabolic precursors which can be converted into osmolyte amino acids by a metabolic step such as transamination. For example, a precursor of the amino acid glutamine is poly-L-glutamine, and a precursor of glutamate is poly-L-glutamic acid.

Mucolytic Combinations with Sodium Channel Blockers:

Coordinated ion transport by the airway epithelia directly regulates the hydration level of the mucosal surface. Importantly, sodium absorption through the epithelial sodium

channel (ENaC) provides the rate-limiting step in hydration. In human subjects with loss of function mutation in ENaC have 'wet' airway surfaces and extraordinarily fast mucous clearance (Kerem et al., N Engl J Med. 1999 Jul 15;341(3):156-62). Conversely, increased sodium absorption through ENaC has been shown to be the underlying cause of mucous dehydration and the formation of mucous plugs in the lungs CF patients. Furthermore, transgenic mice that overexpress ENaC in the lungs have dehydrated airway surfaces and reduced/absent mucous clearance that results in death (Hummler et al., Proc Natl Acad Sci U S A. 1997 Oct 14;94(21):11710-5). As predicted from clinical and experimental data, pharmacological blockade of ENaC conserves liquid on airway surfaces and increases mucus clearance (Hirsh et al., J Pharmacol Exp Ther. 2008; 325(1):77-88). Particular examples include, but are not limited to:

Small molecule channel blockers: Small molecule ENaC blockers are capable of directly preventing sodium transport through the ENaC channel pore. ENaC blocker that can be administered by the methods of this invention include, but are not limited to, amiloride, benzamil, phenamil, and amiloride analogues as exemplified by US Pat. No. 6,858,614, US Pat. No. 6,858,615, US Pat. No. 6,903,105, US Pat. No. 6,995,160, US Pat. No. 7,026,325, US Pat. No. 7,030,117, US Pat. No. 7,064,129, US Pat. No. 7,186,833, US Pat. No. 7,189,719, US Pat. No. 7,192,958, US Pat. No. 7,192,959, US Pat. No. 7,241,766, US Pat. No. 7,247,636, US Pat. No. 7,247,637, US Pat. No. 7,317,013, US Pat. No. 7,332,496, US Pat. No. 7,345,044, US Pat. No. 7,368,447, US Pat. No. 7,368,450, US Pat. No. 7,368,451, US Pat. No. 7,375,107, US Pat. No. 7,399,766, US Pat. No. 7,410,968, US Pat. No. 7,820,678, US Pat. No. 7,842,697, US Pat. No. 7,868,010, US Pat. No. 7,875,619. U.S. Patent 7,956,059, U.S. Patent 8,008,494, U.S. Patent 8,022,210, U. S. Patent 8,124,607, U.S. Patent 8,143,256, U.S Patent 8,163,758, U.S. Patent 8,198,286, U.S. Patent 8,211,895, U.S. Patent 8,324,218 U.S. Patent 8,507,497 U.S. Patent 8,575,176, U. S. Patent 8,669,262 , U.S. Patent 7,956,059, U.S. Patent 8,008,494, U.S. Pt 8,022,210, U. S. Patent 8,124,607, U.S. Patent 8,143,256, U.S Patent 8,163,758, U.S. Patent 8,198,286, U.S. Patent 8,211,895, U.S. Patent 8,324,218 U.S. Patent 8,507,497 U.S. Patent 8,575,176, U. S. Patent 8,669,262, U.S. Patent 7,956,059, U.S. Patent 8,008,494, U.S. Patent 8,846,688, U.S. Patent 8,022,210, U.S. 9,029,382, U.S. Patent 9,072,738, U. S. Patent 9,102,633 U.S. Patent Application Publication No. US2014/0142118-A1, U. S. Patent Application No. US20140170244-A1, and U. S. Patent Application No. US20140171447-A1.

Mucolytic Combinations with Protease inhibitors:

ENaC proteolysis is well described to increase sodium transport through ENaC. Protease inhibitor block the activity of endogenous airway proteases, thereby preventing ENaC cleavage and activation. Protease that cleave ENaC include furin, meprin, matriptase, trypsin, channel associated proteases (CAPs), and neutrophil elastases. Protease inhibitors that can inhibit the proteolytic activity of these proteases that can be administered by the methods of this invention include, but are not limited to, camostat, prostasin, furin, aprotinin, leupeptin, and trypsin inhibitors.

Mucolytic Combinations with Nucleic acids and Small Interfering RNAs (siRNA):

Any suitable nucleic acid (or polynucleic acid) can be used to carry out the present invention, including but not limited to antisense oligonucleotide, siRNA, miRNA, miRNA mimic, antagomir, ribozyme, aptamer, and decoy oligonucleotide nucleic acids. *See, e.g.*, US Patent Application Publication No. 20100316628. In general, such nucleic acids may be from 17 or 19 nucleotides in length, up to 23, 25 or 27 nucleotides in length, or more.

Any suitable siRNA active agent can be used to carry out the present invention. Examples include, but are not limited to, those described in US Patent No. 7,517,865 and US Patent Applications Nos. 20100215588; 20100316628; 20110008366; and 20110104255. In general, the siRNAs are from 17 or 19 nucleotides in length, up to 23, 25 or 27 nucleotides in length, or more.

Mucolytic Combinations with Secretagogues:

Mutations in the cystic fibrosis (CF) gene result in abnormal ion transport across the respiratory epithelium (Matsui et al., *Cell* 1998;95:1005-15). Excessive absorption of sodium and the inability to secrete chloride by the airway epithelium in patients with CF drives water absorption down an osmotic gradient generated by inappropriate salt absorption, dehydrating airway mucous secretions and reducing the volume of liquid in the PCL. In COPD, cigarette smoke impairs CFTR function, thus creating an acquired phenotype similar to CF.

P2Y₂ Receptor Agonists: Agents that that may be administered in combination with the methods and molecules described in the present invention include a group of P2Y₂ agonists. Purinergic (P2Y₂) receptors are abundant on luminal surface of human bronchial epithelium (HBE) and are known to stimulate Cl⁻ secretion and inhibit Na⁺ absorption (Goralski et al., *Curr Opin Pharmacol.* 2010 Jun;10(3):294-9). UTP is an example of an endogenous P2Y₂ receptor agonist that provides a robust stimulation of chloride secretion,

inhibition of sodium absorption and increase in airway surface liquid layer in airway epithelium, thus increasing the mucus clearance which is the primary defense mechanism of the lung. Early studies using uridine-5-triphosphate (UTP) delivered via aerosol to airway surfaces of CF and primary cilia dyskinesia (PCD) patients suggested the usefulness of UTP in enhancing MC and improving mean cough clearance rates.

Suitable P2Y₂ receptor agonists are described in, but are not limited to, U.S. Pat. No. 6,264,975, U.S. Pat.No.5,656,256, U.S. Pat.No.5,292,498, U.S. Pat.No.6,348,589, U.S. Pat.No.6,818,629, U.S. Pat.No.6,977,246, U.S. Pat.No.7,223,744, U.S. Pat.No.7,531,525 and U.S. Pat.AP.2009/0306009 each of which is incorporated herein by reference.

Activators of Alternative Chloride Channels such as CaCCs and ClC-2 Class Channels: CaCCs are broadly expressed in mammalian cells where they are involved in a wide range of physiological functions, including transepithelial fluid secretion, oocyte fertilization, olfactory and sensory signal transduction, smooth muscle contraction, and neuronal and cardiac excitation. Whole cell current analysis indicates several common features between CaCC subfamilies, including slow activation following membrane depolarization, outwardly rectifying steady state currents and greater iodide than chloride permeability. Single channel analysis has suggested four or more distinct CaCC subclasses, with a wide range of reported single channel conductances from less than 2 pS in cardiac myocytes to 50 pS in airway epithelial cells.

The consequences of CaCC activation are cell type specific, for example, chloride secretion in epithelial cells, action potential generation in olfactory receptor neurons, smooth muscle contraction, and prevention of polyspermia in oocytes. In some cell types, such as smooth muscle cells, membrane depolarization activates voltagegated calcium channels, increasing intracellular calcium concentration. Although CaCCs were functionally characterized nearly three decades ago, their molecular identity has remained unclear until recently, with potential candidates including bestrophins (BEST1–BEST4) (Sun et al., *Proc Natl Acad Sci U S A* 99, 4008–4013 (2002) and Tsunenari et al., *J Biol Chem* 278, 41114–41125 (2003)), the calcium activated chloride channel ClCA family proteins (Gruber et al., *Genomics* 1998;54:200–214) and ClC3 (Huang P et al. (2001) Regulation of human CLC-3 channels by multifunctional Ca²⁺/calmodulin-dependent protein kinase. *JBC* 276: 20093-100). Three independent laboratories have identified TMEM16A, also called anoctamin1, as a strong candidate for a CaCC (Yang YD et al. (2008) TMEM16A confers receptor-activated calcium-dependent chloride conductance. *Nature*. 455: 1210-15; Caputo A et al. (2008) TMEM16A, a membrane protein associated with calcium-dependent chloride channel

activity. *Science*. 322: 590-4; Schroeder BC et al. (2008) Expression cloning of TMEM16A as a calcium-activated chloride channel subunit. *Cell*. 134: 1019-29). Three different strategies were used: database searching for membrane proteins with multiple transmembrane segments and unknown function (Yang YD et al. (2008) TMEM16A confers receptor-activated calcium-dependent chloride conductance. *Nature*. 455: 1210-15), functional genomics following the observation that interleukin 4 (IL4) treated bronchial epithelial cells show increased CaCC activity (Caputo A et al. (2008) TMEM16A, a membrane protein associated with calcium-dependent chloride channel activity. *Science*. 322: 590-4), and expression cloning using axolotl oocytes that do not have endogenous CaCC activity (Schroeder BC et al. (2008) Expression cloning of TMEM16A as a calcium-activated chloride channel subunit. *Cell*. 134: 1019-29). There is strong evidence to suggest TMEM16A is a key component of CaCC, including similarity to native CaCCs in its electrophysiological properties, appearance of CaCC currents in various transfected cell systems, reduction in CaCC currents following RNAi knockdown, and its tissue distribution. TMEM16A has eight putative transmembrane segments without domains evidently involved in calcium regulation.

CIC2 is a ubiquitously expressed, inwardly rectifying chloride channel that is activated by cell swelling. CIC2 was thought to be involved in cell volume regulation, but it has different biophysical characteristics from the volume sensitive chloride channels that have been characterized in many tissues. Suitable alternative chloride channel activators are described in U.S. Pat. No. 6015828, 6159969 and 7253295. The therapeutic efficacy of activators of Alternative Chloride Channels such as CaCCs and CIC-2 Class Channels can be enhanced by the administration of compounds and methods of this invention.

Modulators of CFTR activity The hereditary lethal disease cystic fibrosis is caused mutations in the gene encoding CFTR protein, a cAMP activated chloride channel expressed in the airway epithelia. Various mutations in CFTR cause ion transport dysfunction by limiting the chloride ion secretion to the surface of the airway epithelium via CFTR and by dys-regulation of sodium ion absorption, leading to excessive absorption of sodium cations. These defects in ion transport result in impaired hydration of airway surface liquid layer, decrease in mucus clearance and lead to progressive loss of lung function. Recently, it has been shown that CFTR functional defects are present in cigarette smoke exposed tissue, thus implying the role of CFTR dysfunction in COPD.

Over 1500 putative mutations have been described in CFTR, which can be divided into classes according to the molecular mechanism of the genetic defect (Rowe et al., *Pulm*

Pharmacol Ther., 23(4):268-78 (2010)). An understanding of the biology of each of these mutations has led to therapeutic strategies based on the particular mutation type. Class I mutations include premature termination codons (PTCs, e.g. nonsense mutations) within the coding region of CFTR, which cause premature truncation of normal protein translation. These mutations are found in 10% of CF patients, but are particularly common in Ashkenazi Jews (75% of mutant CFTR alleles). Class II CFTR mutations include F508del CFTR, the most common mutation in humans (accounting for 75% of alleles and found in approximately 90% of CF patients). The deletion of phenylalanine at the 508 position causes CFTR to exhibit abnormal folding characterized by deficient stabilization by domain–domain interactions between the nucleotide binding domain 1 (NBD1) and the transmembrane domains. The misfolded protein is recognized by cellular chaperones within the endoplasmic reticulum (ER), directed to the proteasome, and rapidly degraded prior to reaching its active site at the cell surface. Because the cellular machinery responsible for the recognition and degradation of the misfolded protein is not 100% efficient, particular individuals exhibit low levels of surface expression of F508del CFTR, which may account for partial CFTR activity (and a more mild CF phenotype) observed in individuals homozygous for F508del CFTR, and could represent a population more amenable to protein repair. Even when at the cell surface, F508del CFTR exhibits reduced gating, suggesting that misfolded CFTR also exhibits reduced CFTR ion channel activity. Class III and IV CFTR mutations are characterized by full-length CFTR that reaches the cell surface but exhibit reduced ion transport activity owing to abnormal channel gating (Class III, e.g. G551D) or reduced conductivity of the ion channel pore (Class IV, e.g. R117H). Similarly, splicing mutants (Class V) and mutations within the C-terminus (Class VI) are also full length, but exhibit reduced activity owing to reduced numbers of active channels within the plasma membrane. Although the molecular basis of CFTR mutants is complex and as yet incomplete, the classification of CFTR mutants can be simplified into the therapeutically relevant groups based on the activity of agents in development. Both traditional and high-throughput drug discovery programs have resulted in discovery of novel compounds that address specific mutant CFTR alleles. These ‘CFTR modulators’ are pharmacological agents intended to repair the CFTR protein and are described in each section that follows.

Potentiators of cell-surface cystic fibrosis transmembrane conductance regulator CFTR mutation classes that result in dysfunctional CFTR that resides at the plasma membrane include Class III, IV, V, and VI mutations and represent potential targets for CFTR activators. G551D CFTR represents an archetype CFTR allele for this category of

agents, as it exhibits normal surface expression and half-life, but confers a severe defect in channel gating owing to an amino acid substitution in the adenosine triphosphate (ATP) binding pocket within the nucleotide binding domains (Gregory, R.J. et al. (1991) Maturation and function of cystic fibrosis transmembrane conductance regulator variants bearing mutations in putative nucleotide-binding domains 1 and 2. *MCB* 11: 3886-93; Bompadre, S.G. et al. (2007) G551D and G1349D, two CF-associated mutations in the signature sequences of CFTR, exhibit distinct gating defects. *Gen Physiol.* 129: 285-298). Flavonoids are well known activators of mutant CFTR and were among the first to be studied for beneficial effects in human individuals (including topical administration). Although agents such as genistein were affected by lack of efficacy in the nasal airway, more recent efforts have demonstrated activity of the flavonoid quercetin in the nose. However, flavonoid agents are challenged by poor solubility and systemic absorption, and are poor development candidates for inhaled therapeutics. More recent discovery strategies have focused on identification of compounds that 'potentiate' CFTR activity, restoring endogenous regulation (e.g. cyclic adenosine monophosphate (cAMP)-dependent regulation) and ion transport without excessive, constitutive activation that may potentially be detrimental (such as excessive CFTR activation seen with certain diarrheal illnesses). Identification of agents of this type is amenable to high-throughput screening-based strategies to discover agents that activate mutant CFTR by measuring the effects on anion conductance in cell-based screening assays. A number of specific strategies have been used for screens of this sort, including chloride sensitive dyes, fluorescence resonance energy transfer-based analysis of membrane potential, and cell conductance of airway monolayers. Identification and characterization of small molecule potentiators of mutant CFTR have led to the development of agents with pronounced activity *in vitro* and in the clinic.

Significant effort has been directed toward the goal of correcting the folding of F508del CFTR, thus restoring ion channel activity to the misfolded protein. A diverse array of cellular targets have been explored, commensurate with the large number of proteins now known to interact with CFTR biogenesis. Agents such as 4-phenyl butyrate downregulate Hsc70 (or other cell chaperones) central to the folding process, and represent an early example of compounds tested in the clinic. Other more recent efforts have resulted from high-throughput library screens for chloride channel function following incubation of test compounds with F508del expressing cells. A number of these strategies have identified F508del correctors that may address cell biogenesis through chaperone pathways. Pharmacologic activity of such agents has also been reported to augment F508del CFTR half-

life in the plasma membrane through altered surface recycling attributed to features of the cellular processing machinery or reduced endocytic trafficking. This class of agents may be potential drug development candidates if their safety *in vivo* is confirmed. Other compounds have been shown to directly interact with CFTR and may offer greater specificity than agents that alter general aspects of cell folding or cellular quality control. The global cellular response to misfolded protein may also represent a target. Histone deacetylases (HDAC) have far-ranging effects on gene expression, and specific members of the HDAC family are involved in the ER associated degradation pathway promoting degradation of F508del CFTR. Treatment of CF cells with HDAC inhibitors can modulate ER stress, and HDACs such as suberoylanilidehydroxamic acid, as well as siRNA-silencing of HDACs, increase levels of F508del CFTR in the cell membrane. The combination of approaches such as these reveal a number of potential pharmacologic agents for F508del correction. Additive or synergistic rescue of F508del CFTR using more than one such strategy may offer hope of achieving ion transport activity sufficient to confer a normal phenotype in CF respiratory epithelia.

Read-through of premature termination codons (PTCs) represents another exciting approach to address the underlying cause of CF, and many other genetic diseases caused by PTCs. Certain aminoglycosides and other agents have the capacity to interact with the eukaryotic rRNA within the ribosomal subunits. Although this interaction is much weaker than that seen in prokaryotes and is distinct from the primary cause of aminoglycoside toxicity in human individuals, it can modestly reduce the fidelity of eukaryotic translation by interrupting the normal proofreading function of the ribosome. Insertion of a near cognate amino acid at a premature stop codon allows protein translation to continue until one of several stop codons normally present at the end of the mRNA transcript is reached and properly utilized. The specificity of the strategy has been attributed to greater stop codon fidelity at the authentic end of mRNA and has been established *in vitro* by demonstrating no detectable elongation beyond native stop codons.

CFTR activity modulating compounds that can be administered in combination with the methods and molecules described in the present invention include, but are not limited to, compounds described in US 2009/0246137 A1, US 2009/0253736 A1, US 2010/0227888 A1, US 7645789, US 2009/0246820 A1, US 2009/0221597 A1, US 2010/0184739 A1, US 2010/0130547 A1, US 2010/0168094 A1, US 7553855, US 7,772,259 B2, US 7,405,233 B2, US 2009/0203752, and US 7,499,570.

Mucolytic Combinations with Anti-infective Agents:

Chronic obstructive pulmonary diseases are accompanied by both acute and chronic bacterial infections. Both acute and chronic infections lead to chronic inflammation that has acute flare-ups in the form of pulmonary exacerbations. The underlying inflammation is treated with variety of inhaled anti-inflammatory agents. For example, in cystic fibrosis the most common bacteria causing chronic infection is *Pseudomonas aeruginosa* (*P. aeruginosa*) and antibiotics that are effective against this bacteria are a major component of treatment (Flume, Am J Respir Crit Care Med. 176(10):957-69 (2007)). Also bacteria such as *Staphylococcus aureus* (*S. aureus*), *Burkholderia cepacia* (*B. cepacia*) and other gram negative organisms as well as anaerobes are isolated from respiratory secretions and people with CF may benefit from treatment of these pathogens to maintain their lung health. Anaerobic bacteria are also recognized as a feature of CF airways, sinuses in subjects with chronic sinusitis, and likely airways of subjects with COPD. Similarly, aspirations or microaspirations, especially in elderly population and during sleep, are associated with a chemical pneumonitis, anaerobic infections and subsequent bronchiectasis. An ideal treatment of aspiration-related pneumonitis and anaerobic infection would be an immediate treatment. As such, antibiotics are used to eradicate early infections, during pulmonary exacerbations and as chronic suppressive therapy.

The primary measure of antibiotic activity is the minimum inhibitory concentration (MIC). The MIC is the lowest concentration of an antibiotic that completely inhibits the growth of a microorganism *in vitro*. While the MIC is a good indicator of the potency of an antibiotic, it indicates nothing about the time course of antimicrobial activity. PK parameters quantify the lung tissue level time course of an antibiotic. The three pharmacokinetic parameters that are most important for evaluating antibiotic efficacy are the peak tissue level (C_{max}), the trough level (C_{min}), and the Area Under the tissue concentration time Curve (AUC). While these parameters quantify the tissue level time course, they do not describe the killing activity of an antibiotic.

Integrating the PK parameters with the MIC gives us three PK/PD parameters which quantify the activity of an antibiotic: the Peak/MIC ratio, the T>MIC, and the 24h-AUC/MIC ratio. The Peak/MIC ratio is simply the C_{pmax} divided by the MIC. The T>MIC (time above MIC) is the percentage of a dosage interval in which the serum level exceeds the MIC. The 24h-AUC/MIC ratio is determined by dividing the 24-hour-AUC by the MIC. The three pharmacodynamic properties of antibiotics that best describe killing activity are time-dependence, concentration-dependence, and persistent effects. The rate of killing is determined by either the length of time necessary to kill (time-dependent), or the effect of

increasing concentrations (concentration-dependent). Persistent effects include the Post-Antibiotic Effect (PAE). PAE is the persistent suppression of bacterial growth following antibiotic exposure.

Using these parameters, antibiotics can be divided into 3 categories:

Pattern of Activity	Antibiotics	Goal of Therapy	PK/PD Parameter
Type I Concentration-dependent killing and Prolonged persistent effects	Aminoglycosides Daptomycin Fluoroquinolones Ketolides	Maximize concentrations	24h-AUC/MIC Peak/MIC
Type II Time-dependent killing and Minimal persistent effects	Carbapenems Cephalosporins Erythromycin Linezolid Penicillins	Maximize duration of exposure	T>MIC
Type III Time-dependent killing and Moderate to prolonged persistent effects.	Azithromycin Clindamycin Oxazolidinones Tetracyclines Vancomycin	Maximize amount of drug	24h-AUC/MIC

For Type I antibiotics (AG's, fluoroquinolones, daptomycin and the ketolides), the ideal dosing regimen would maximize concentration, because the higher the concentration, the more extensive and the faster is the degree of killing. Therefore, the 24h-AUC/MIC ratio, and the Peak/MIC ratio are important predictors of antibiotic efficacy. For aminoglycosides, it is best to have a Peak/MIC ratio of at least 8-10 to prevent resistance. For fluoroquinolones vs gram negative bacteria, the optimal 24h-AUC/MIC ratio is approximately 125. Versus gram positives, 40 appears to be optimal. However, the ideal 24h-AUC/MIC ratio for FQ's varies widely in the literature.

Type II antibiotics (beta-lactams, clindamycin, erythromycin, carbapenems and linezolid) demonstrate the complete opposite properties. The ideal dosing regimen for these antibiotics maximizes the duration of exposure. The $T > MIC$ is the parameter that best correlates with efficacy. For beta-lactams and erythromycin, maximum killing is seen when the time above MIC is at least 70% of the dosing interval.

Type III antibiotics (vancomycin, tetracyclines, azithromycin, and the dalfopristin-quinupristin combination) have mixed properties, they have time-dependent killing and moderate persistent effects. The ideal dosing regimen for these antibiotics maximizes the amount of drug received. Therefore, the 24h-AUC/MIC ratio is the parameter that correlates with efficacy. For vancomycin, a 24h-AUC/MIC ratio of at least 125 is necessary.

Patients including, but not limited to, CF, COPD, non-CF bronchiectasis, aspiration pneumonia, asthma and VAP patients suffering from respiratory infection caused by bacteria susceptible to meropenem may benefit from such treatment. Examples of carbapenem antibiotics are: imipenam, panipenam, meropenam, doripenem, biapenam, MK-826, DA-1131, ER-35786, lenapenam, S-4661, CS-834 (prodrug of R-95867), KR-21056 (prodrug of KR-21012), L-084 (prodrug of LJC 11036) and CXA-101. The therapeutic efficacy of all anti-infective agents described can be enhanced by the pre- or co-administration of compounds and methods of this invention.

Mucolytic Combinations with Exemplary Anti-Inflammatory Agents:

Inhaled corticosteroids are the standard of chronic care for asthma, COPD and other respiratory diseases characterized by acute and chronic inflammation leading to airflow limitation. Examples of anti-inflammatory agents suitable for administration in combination with the methods and molecules described in the present invention include beclomethasone, budesonide, and fluticasone and a group of anti-inflammatory medications that do not contain steroids known as non-steroidal anti-inflammatory drugs (NSAIDs).

Products of arachidonic acid metabolism, specifically the leukotrienes (LTs), contribute to pulmonary inflammation. Cysteinylleukotrienes (LTC₄, LTD₄, and LTE₄) are produced predominantly by eosinophils, mast cells, and macrophages. Examples of leukotriene modifiers suitable for administration by the method of this invention include monteleukast, zileuton and zafirlukast.

Mast cell stabilizers are cromone medications such as cromolyn (sodium cromoglycate) used to prevent or control certain allergic disorders. They block a calcium channel essential for mast cell degranulation, stabilizing the cell and thereby preventing the

release of histamine and related mediators. As inhalers they are used to treat asthma, as nasal sprays to treat hay fever (allergic rhinitis) and as eye drops for allergic conjunctivitis. Finally, in oral form they are used to treat the rare condition of mastocytosis.

PDE4 inhibitors have been shown to modulate pulmonary inflammation and used for treatment of chronic obstructive pulmonary diseases. Examples of PDE4 inhibitors suitable for use in combination with the methods and molecules described in the present invention include, but is not limited to theophylline and roflumilast.

Mucolytic Combinations with Exemplary Bronchodilators:

Nitric Oxide (NO) Donors: NO, NO Donors, NO and Peroxynitrite Scavengers and Inducible NO Synthase Activity Modulators. Nitric oxide is a potent endogenous vasodilator and bronchodilator that can be exogenously administered via inhalation. It is synthesized by the conversion of the terminal guanidine nitrogen atom of L-arginine via endothelial cell calcium dependent enzyme nitric oxide synthetase and then diffuses across the cell membrane to activate the enzyme guanylatecyclase. This enzyme enhances the synthesis of cyclic guanosine monophosphate (cGMP), causing relaxation of vascular and bronchial smooth muscle and vasodilatation of blood vessels (Palmer, *Circ Res.*, 82(8):852-61 (1998)).

Nitric oxide synthesised in endothelial cells that line blood vessels has a wide range of functions that are vital for maintaining a healthy respiratory and cardiovascular systems (Megson IL et al *Expert Opin Investig Drugs*. 2002 May;11(5):587-601.). Reduced nitric oxide availability is implicated in the initiation and progression of many diseases and delivery of supplementary nitric oxide to help prevent disease progression is an attractive therapeutic option. Nitric oxide donor drugs represent a useful means of systemic nitric oxide delivery and organic nitrates have been used for many years as effective therapies for symptomatic relief from angina. However, nitrates have limitations and a number of alternative nitric oxide donor classes have emerged since the discovery that nitric oxide is a crucial biological mediator.

In the respiratory tract, NO is produced by residential and inflammatory cells (Ricciardolo FL et al. *Curr Drug Targets* 2006 Jun;7(6):721-35). NO is generated via oxidation of L-arginine that is catalysed by the enzyme NO synthase (NOS). NOS exists in three distinct isoforms: neuronal NOS (nNOS), inducible NOS (iNOS), and endothelial NOS (eNOS). NO derived from the constitutive isoforms of NOS (nNOS and eNOS) and other NO-adduct molecules (nitrosothiols) are able to modulate bronchomotor tone. NO derived from the inducible isoform of NO synthase, up-regulated by different cytokines via NF-

kappaB-dependent pathway, seems to be a pro-inflammatory mediator with immunomodulatory effects. In aging CF patients, expression of iNOS is significantly reduced (Yoon et al., J Clin Invest. 2006 Feb;116(2):436-46). This reduced expression of iNOS in chronic CF is associated with emergence of mucoid *muc* mutant subpopulation of *P. aeruginosa*. It has been suggested that 15 mM NO₂⁻ kills *mucA P. Aeruginosa* in CF airways at pH 6.5. NO itself or as a precursor to iron-nitrosyl species has been implicated in this antimicrobial effect. Therefore inhaled NO₂⁻, including but not limited inhaled NaNO₂, has an appeal as a CF therapy. The production of NO under oxidative stress conditions secondarily generates strong oxidizing agents (reactive nitrogen species) that may amplify the inflammatory response in asthma and COPD. Moreover, NO can be exhaled and levels are abnormal in stable atopic asthma and during exacerbations in both asthma and COPD. Exhaled NO might therefore be a non-invasive tool to monitor the underlying inflammatory process. It is suggested that NOS regulation provides a novel target in the prevention and treatment of chronic inflammatory diseases of the airways such as asthma and COPD.

Examples of NO, NO donors and NO synthase activity modulators suitable for administration in combination with the methods and molecules described in the present invention include inhaled NO, agents disclosed in Vallance et al. *Fundam Clin Pharmacol.* 2003 Feb;17(1):1-10, Al-Sa'doni HH et al. *Mini Rev Med Chem.* 2005 Mar;5(3):247-54, Miller MR et al. *Br J Pharmacol.* 2007 Jun;151(3):305-21. Epub 2007 Apr 2 and Katsumi H et al. *Cardiovasc Hematol Agents Med Chem.* 2007 Jul;5(3):204-8.

Under certain conditions, inducible NO synthase activity leads to overproduction of NO which in turn increases inflammation and tissue injury. Under these conditions, the following inducible NO synthase inhibitors, NO scavengers and peroxynitrite scavengers administered in combination with the methods and molecules described in the present invention are suitable: Bonnefous et al. *J. Med. Chem.*, 2009, 52 (9), pp 3047–3062, Muscara et al *AJP - GI June 1999 vol. 276 no. 6 G1313-G1316* or Hansel et al. *FASEB Journal.* 2003;17:1298-1300.

Beta 2-adrenergic receptor agonists: It has been established that administration of super-therapeutic concentrations of receptor agonists leads to receptor desensitization and loss of efficacy. For example, this phenomenon has been described for beta 2-adrenoceptor based bronchodilator agents (Düringer et al., Br J Pharmacol., 158(1):169-79 (2009)). High concentration of these receptor agonist agents leads to the receptor phosphorylation, internalization and potential degradation. Administration of receptor agonists, which cause

tachyphylaxis following bolus administration via fast nebulizer, by inhalation over the course of 8 to 24 hours or overnight to a patient via nasal cannula improves the efficacy of such agents due to decreased extent of tachyphylaxis. Beta 2-adrenergic receptor agonists include albuterol, levalbuterol, salbutamol, procaterol, terbutaline, pirbuterol, and metaproterenol. The therapeutic efficacy of beta 2-adrenergic receptor agonists can be enhanced by the pre- or co-administration of compounds and methods of this invention.

Mucolytic Combinations with Exemplary Gene Carriers:

Examples of gene carriers for the administration of gene therapy include viruses, DNA:protein complexes, plasmids, DNAs, and RNAs.

Mucolytic Combinations with Other Exemplary Therapeutic Agents:

Examples of other classes of therapeutic agents suitable for administration in combination with the methods and molecules described in the present invention include antivirals such as ribavirin, anti-fungal agents such as amphotericin, itraconazole and voriconazole, immunosuppressants, anti-rejection drugs such as cyclosporine, tacrolimus and sirolimus, bronchodilators including but not limited to anticholinergic agents such as ipratropium, tiotropium, aclidinium and others, PDE5 inhibitors siRNAs, gene therapy vectors, aptamers, endothelin-receptor antagonists, alpha-1-antitrypsin, prostacyclins, vaccines, PDE-4 and PDE-5 inhibitors and steroids such as beclomethasone, budesonide, ciclesonide, flunisolide, fluticasone, mometasone and triamcinolone.

EXPERIMENTAL PROCEDURES AND BIOLOGICAL ASSAYS:

Materials and Methods

All commercial materials were used as supplied unless otherwise noted. All solvents were reagent grade or HPLC grade. Anhydrous THF, MeOH, CH₂Cl₂ were purchased from Sigma-Aldrich and used without further drying. All reactions were performed under an atmosphere of pre-purified dry Ar(g). NMR spectra were recorded on Bruker Avance-400 instrument and Solvents CDCl₃, CD₃OD and DMSO-*d*₆ were purchased from Aldrich or Cambridge Isotope Laboratories, unless otherwise specified. The following abbreviations were used to explain the multiplicities: s=singlet, d=doublet, t=triplet, q=quartet, m=multiplet, and br=broad. Chemical shifts are reported in ppm relative to tetramethylsilane (TMS) as the internal standard. Microwave reactions were performed on a Biotage microwave reactor. All reactions were carried out in oven-dried glassware under argon atmosphere unless otherwise

noted. Reactions were monitored by TLC carried out on 0.25 mm E. Merck silica-gel plates (60F-254) by using UV light as visualizing agent and ninhydrin solution and heat as developing agents. For polar compounds reactions are monitored by HPLC and LCMS analysis. E. Merck silica gel (60, particle size 0.040–0.063 mm) was used for flash-column chromatography.

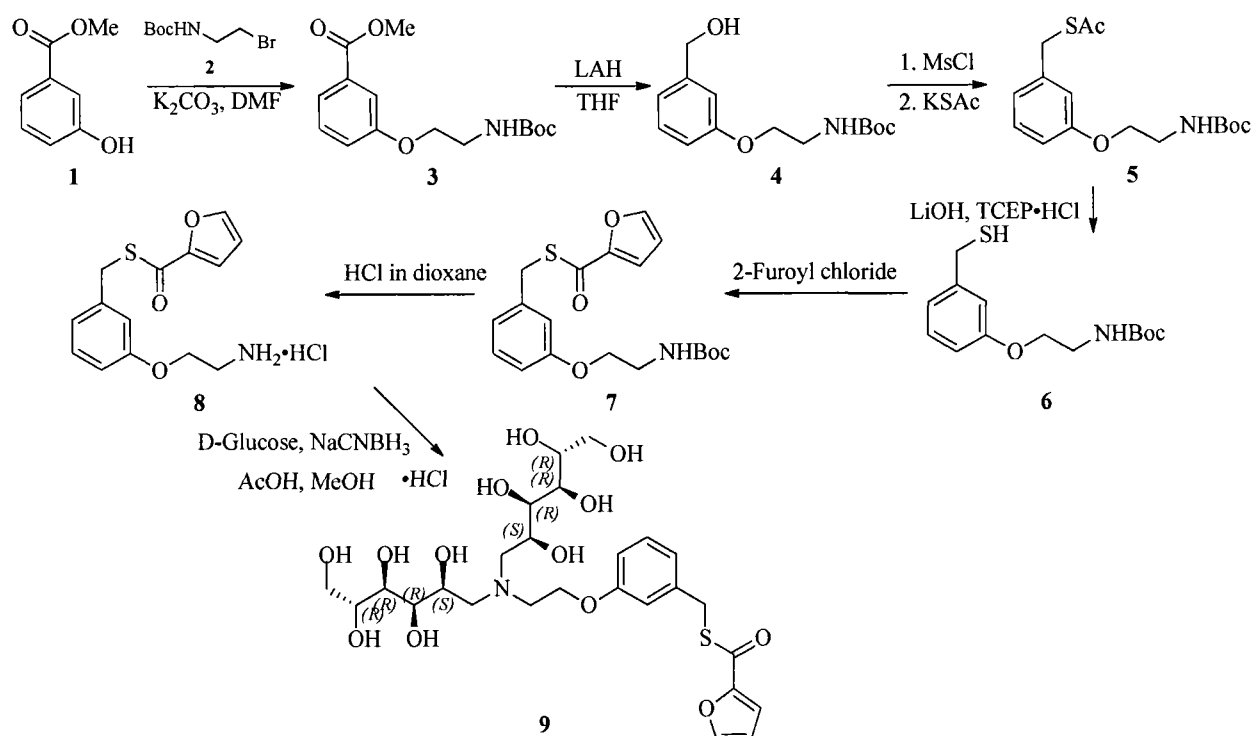
LCMS and HPLC Method:

LCMS analyses were obtained using a Sunfire C18, 2.1x50 mm Analytical Column detected at 254 nm (unless otherwise specified) on a Shimadzu LCMS-LC-20AD. The following time program was used with a flow rate of 0.40 mL per minute.

HPLC analyses were obtained using XTerra MS C18 Column 5 μ 4.6 x 150 mm Analytical Column detected at 220 nm (unless otherwise specified) on a Shimadzu HPLC system.

1. Preparation of *S*-3-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl furan-2-carbothioate hydrochloride (9);

Scheme 1



Preparation of methyl 3-(2-((tert-butoxycarbonyl)amino)ethoxy)benzoate (3); A solution of compound 1 (10.5 g, 69.0 mmol) in DMF (40 mL) was charged with K₂CO₃ (19.0 g, 138 mmol) and stirred at room temperature for 5 min. The above reaction mixture was charged

with compound **2** (24.1 g, 104 mmol) and the reaction mixture was stirred at room temperature for 48 h. The reaction mixture was diluted with water (300 mL) and extracted with EtOAc (3 × 300 mL). The combined organic layers were concentrated and the residue was purified by column chromatography to afford compound **3** (18.0 g, 89%) as a white gum: ¹H NMR (400 MHz, CDCl₃) δ 7.62 (dt, *J* = 8.0, 1.3 Hz, 1H), 7.56–7.52 (m, 1H), 7.34 (t, *J* = 7.9 Hz, 1H), 7.10–7.06 (m, 1H), 5.04 (brs, 1H), 4.06 (t, *J* = 5.2 Hz, 2H), 3.90 (s, 3H), 3.58–3.50 (m, 2H), 1.45 (s, 9H); ESI MS *m/z* 296 [M + H]⁺.

Preparation of *tert*-butyl (2-(3-(hydroxymethyl)phenoxy)ethyl)carbamate (4); A solution of compound **3** (18.0 g, 61.0 mmol) in THF (500 mL) was charged with lithium aluminum hydride (3.50 g, 91.5 mmol) added in small portions over 15 minutes at 0 °C. The resulting reaction mixture was stirred at 0 °C for 1 h and quenched with ice-cold water at 0 °C. The reaction mixture was diluted with EtOAc (300 mL) and filtered through a Celite pad, and the Celite pad was washed with EtOAc (2 × 300 mL). The filtrate was concentrated under vacuum and it was purified by column chromatography to afford compound **4** (14.0 g, 86%) as a gummy solid: ¹H NMR (400 MHz, CD₃Cl) δ 7.26 (t, *J* = 6.9 Hz, 1H), 6.96–6.90 (m, 2H), 6.80 (dd, *J* = 8.5, 2.5 Hz, 1H), 5.10 (brs, 1H), 4.65 (s, 2H), 4.01 (t, *J* = 5.1 Hz, 2H), 3.55–3.45 (m, 2H), 1.97 (brs, 1H), 1.44 (s, 9H); ESI MS *m/z* 268 [M + H]⁺.

Preparation of *S*-3-(2-((*tert*-butoxycarbonyl)amino)ethoxy)benzyl ethanethioate (5); A solution of **4** (14.0 g, 52.4 mmol) in CH₂Cl₂ (500 mL) was charged with Et₃N (21.5 mL, 157 mmol) followed by methanesulfonyl chloride (6.00 mL, 78.6 mmol) at 0 °C and stirred at room temperature for 1 h. The reaction mixture was diluted with water (100 mL) and extracted with CH₂Cl₂ (3 × 150 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄, and concentrated to afford the mesylated product (20.0 g, crude) as yellow oil, which was directly used for the next step without further purification: ESI MS *m/z* 346 [M + H]⁺.

The crude mesylate (20.0 g) in DMF (50 mL) and THF (250 mL) was charged with KSAc (9.00 g, 78.8 mmol) and stirred at room temperature for 16 h. The solvent was removed and the residue was partitioned between water (100 mL) and EtOAc (100 mL). The EtOAc layer was separated and the aqueous layer was extracted with EtOAc (2 × 100 mL). The combined organic layers were concentrated and the residue purified by column chromatography to afford compound **5** (22.0 g, 62% over two steps) as a yellow solid: ¹H NMR (400 MHz, CD₃Cl) δ 7.19 (t, *J* = 7.7 Hz, 1H), 6.87 (dd, *J* = 7.6, 1.5 Hz, 1H), 6.83–6.80 (m, 1H), 6.76

(dd, $J = 6.8, 2.7$ Hz, 1H), 4.99 (brs, 1H), 4.08 (s, 2H), 3.99 (t, $J = 5.1$ Hz, 2H), 3.56–3.44 (m, 2H), 2.34 (s, 3H), 1.45 (s, 9H); ESI MS m/z 326 $[M + H]^+$.

Preparation of *tert*-butyl (2-(3-(mercaptomethyl)phenoxy)ethyl)carbamate (6);

A solution of **5** (4.00 g, 12.7 mmol) in a mixture of THF (20 mL), methanol (20 mL), and water (20 mL) was charged with solid LiOH·H₂O (1.06 g, 25.4 mmol) and the reaction mixture was stirred at room temperature for 1 h. The above reaction mixture was charged with TCEP·HCl (1.81 g, 6.34 mmol) and stirred for another 1 h. The solvent was removed, the residue was dissolved in EtOAc (50 mL), and the solution was washed with saturated aqueous NaHCO₃ solution (40 mL). The EtOAc layer was separated and the aqueous layer was extracted with EtOAc (2 × 150 mL). The combined organic layers were dried over Na₂SO₄, filtered, and concentrated to get crude thiol **6** (3.40 g, 95%, yellow liquid) and used directly for the next step without further purification. ¹H NMR (400 MHz, CD₃Cl) δ 7.22 (t, $J = 8.3$ Hz, 1H), 6.91 (dd, $J = 8.1, 1.1$ Hz, 1H), 6.88–6.85 (m, 1H), 6.76 (dd, $J = 8.5, 2.3$ Hz, 1H), 4.98 (brs, 1H), 4.01 (t, $J = 5.5$ Hz, 2H), 3.70 (t, $J = 7.6$ Hz, 2H), 3.56–3.48 (m, 2H), 1.76 (t, $J = 7.6$ Hz, 1H), 1.45 (s, 9H);

ESI MS m/z 284 $[M + H]^+$.

Preparation of *S*-3-(2-((*tert*-butoxycarbonyl)amino)ethoxy)benzyl furan-2-carbothioate (7); To a solution of compound **6** (3.40 g, 12.0 mmol) and Et₃N (5.05 mL, 36.0 mmol) in CH₂Cl₂ (60 mL) was added 2-furoyl chloride (1.78 mL, 18.0 mmol) 0 °C dropwise and stirred at rt for 1h. Water (20 mL) was added to the reaction mixture and extracted with CH₂Cl₂ (3 × 60 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄, filtered, concentrated and the residue purified by column chromatography to afford compound **7** (4.40 g, 97%) as a colorless liquid: ¹H NMR (400 MHz, CD₃Cl) δ 7.58–7.54 (m, 1H), 7.24–7.17 (m, 2H), 6.95 (dd, $J = 7.6, 1.1$ Hz, 1H), 6.92–6.88 (m, 1H), 6.77 (dd, $J = 8.2, 2.3$ Hz, 1H), 6.52 (dd, $J = 3.5, 1.5$ Hz, 1H), 4.99 (brs, 1H), 4.25 (s, 2H), 4.00 (t, $J = 4.4$ Hz, 2H), 3.56–3.37 (m, 2H), 1.44 (s, 9H); ESI MS m/z 378 $[M + H]^+$.

Preparation of *S*-3-(2-aminoethoxy)benzyl furan-2-carbothioate hydrochloride (8);

Compound **7** (4.40 g, 11.7 mmol) was dissolved in 4 N HCl in dioxane (50 mL) at room temperature and the solution was stirred for 1 h. After concentration, the residue was triturated with EtOAc and isolated by filtration to afford the hydrochloric acid salt **8** (3.40g, 93%) as an off-white solid: ¹H NMR (400 MHz, CD₃OD) δ 7.77–7.74 (m, 1H), 7.26 (dd, $J =$

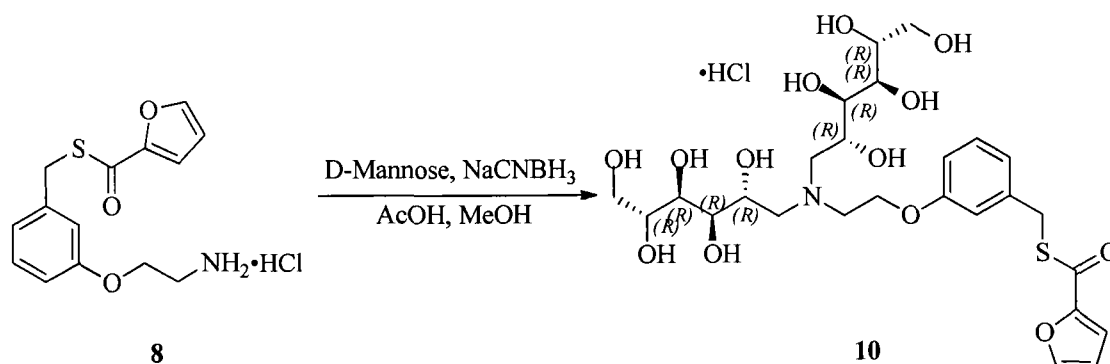
3.9, 1.2 Hz, 1H), 7.24 (d, $J = 8.0$ Hz, 1H), 7.04–7.02 (m, 1H), 7.00 (dd, $J = 7.8, 1.1$ Hz, 1H), 6.89 (ddd, $J = 8.3, 2.7, 1.1$ Hz, 1H), 6.64 (dd, $J = 3.7, 1.1$ Hz, 1H), 4.27 (s, 2H), 4.21 (dd, $J = 4.8, 2.1$ Hz, 2H), 3.34 (dd, $J = 4.8, 1.2$ Hz, 2H); ESI MS m/z 278 $[M + H]^+$.

Preparation of *S*-3-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl furan-2-carbothioate hydrochloride {9});

A solution of amine **8** (1.00 g, 3.20 mmol) in methanol (50 mL) was charged with D-glucose (2.30 g, 12.7 mmol) and acetic acid (0.76 mL, 12.7 mmol) followed by sodium cyanoborohydride (800 mg, 12.7 mmol) and the resulting reaction mixture was heated 50 °C and stirred at 50 °C for 4 h. Additional, D-glucose (0.58 g, 3.20 mmol), acetic acid (0.19 mL, 3.20 mmol) and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting reaction mixture was stirred at 50 °C for another 1 h. The solvent was removed under reduced pressure and the residue purified by reverse-phase chromatography using a C18 Gold column. The pH of product fractions was adjusted to pH = 3 using 4 N HCl water, then were combined and the solvent removed by lyophilization to provide HCl salt **9** (1.20 g, 59%) as an off-white solid: ^1H NMR (400 MHz, CD_3OD) δ 7.76–7.74 (m, 1H), 7.27 (dd, $J = 3.4, 1.4$ Hz, 1H), 7.24 (t, $J = 7.8$ Hz, 1H), 7.06 (d, $J = 1.2$ Hz, 1H), 7.01 (d, $J = 7.4$ Hz, 1H), 6.93 (dd, $J = 8.5, 2.8$ Hz, 1H), 6.64 (dd, $J = 3.8, 1.9$ Hz, 1H), 4.44–4.38 (m, 2H), 4.27 (s, 2H), 4.26–4.18 (m, 2H), 3.97–3.50 (m, 16H); ^1H NMR (400 MHz, $\text{DMSO}-d_6$) δ 8.85–8.68 (m, 1H), 8.03 (d, $J = 1.0$ Hz, 1H), 7.41 (d, $J = 3.7$ Hz, 1H), 7.26 (t, $J = 7.8$ Hz, 1H), 7.00 (d, $J = 8.0, 1.5$ Hz, 2H), 6.91 (dd, $J = 7.9, 1.8$ Hz, 1H), 6.76 (dd, $J = 3.8, 1.6$ Hz, 1H), 5.21–4.50 (m, 11H), 4.44–4.31 (m, 2H), 4.28 (s, 2H), 4.23–4.16 (m, 1H), 4.13–3.99 (m, 2H), 3.84–3.22 (m, 16H); ESI MS m/z 606 $[\text{C}_{26}\text{H}_{39}\text{NO}_{13}\text{S} + \text{H}]^+$.

2. Preparation of Compound *S*-3-(2-(bis((2*R*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl furan-2-carbothioate hydrochloride (10);

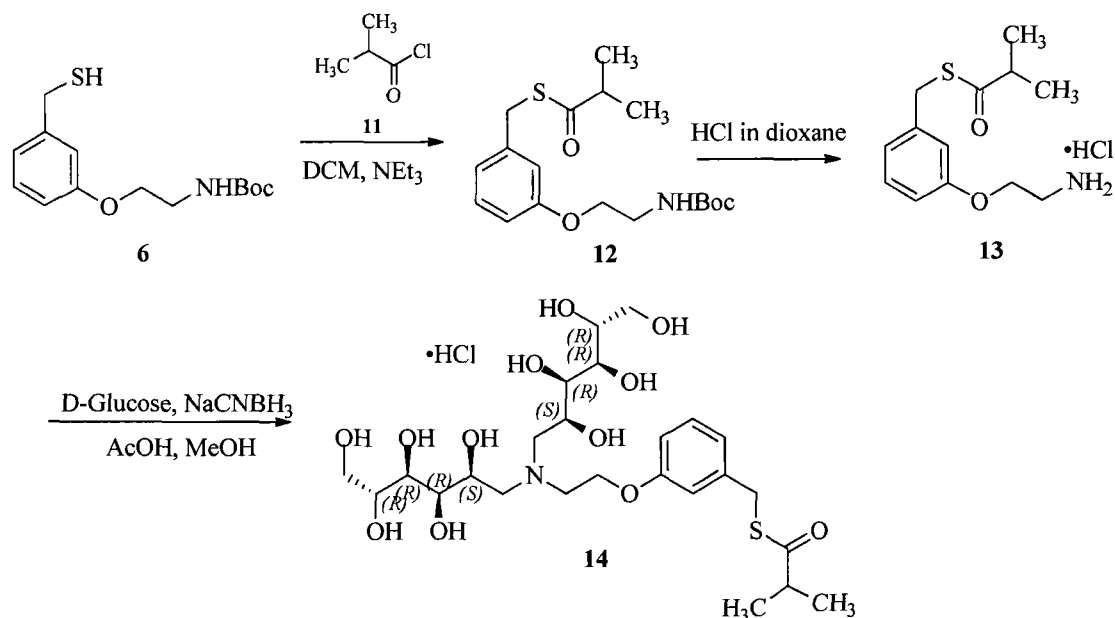
Scheme 2



A solution of amine **8** (1.00 g, 3.20 mmol) in methanol (50 mL) was charged with D-mannose (2.30 g, 12.7 mmol) and acetic acid (0.76 mL, 12.7 mmol) followed by sodium cyanoborohydride (800 mg, 12.7 mmol) and the resulting mixture was heated and stirred at 50 °C for 4 h. Additional, D-mannose (0.58 g, 3.20 mmol), acetic acid (0.19 mL, 3.20 mmol) and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting reaction mixture was heated at 50 °C for an additional 1 h. At that time additional, D-mannose (0.58 g, 3.20 mmol), acetic acid (0.19 mL, 3.20 mmol) and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting mixture was heated at 50 °C for 1 h. The reaction mixture was cooled to rt and water (20 mL) was added; after solvent was removed under reduced pressure, additional water was added (20 mL) then solid precipitation fell out of solution and was filtered through filter paper and washed with water/methanol to get free base of **10**. The free base was then acidified with 4 N HCl in water to make HCL salt and lyophilized to provide **10** (1.38 g, 67) as an off-white solid. ¹H NMR (400 MHz, CD₃OD) δ 7.77–7.74 (m, 1H), 7.27 (dd, *J* = 3.8, 0.8 Hz, 1H), 7.24 (t, *J* = 8.2 Hz, 1H), 7.06 (d, *J* = 1.8 Hz, 1H), 7.01 (d, *J* = 7.6 Hz, 1H), 6.94 (dd, *J* = 8.2, 2.4 Hz, 1H), 6.64 (dd, *J* = 3.9, 1.7 Hz, 1H), 4.46–4.36 (m, 2H), 4.27 (s, 2H), 4.19–4.08 (m, 2H), 3.94–3.59 (m, 14H), 3.55–3.43 (m, 2H); ¹H NMR (400 MHz, DMSO-*d*₆) δ 8.87–8.68 (m, 1H), 8.05–8.01 (m, 1H), 7.41 (d, *J* = 3.6 Hz, 1H), 7.26 (t, *J* = 7.8 Hz, 1H), 7.05–7.00 (m, 1H), 6.99 (d, *J* = 8.2 Hz, 1H), 6.96–6.89 (m, 1H), 6.75 (dd, *J* = 3.7, 1.9 Hz, 1H), 5.40–4.52 (m, 8H), 4.46–4.33 (m, 2H), 4.28 (s, 2H), 4.22–3.82 (m, 5H), 3.97–3.16 (m, 15H); ESI MS *m/z* 606 [C₂₆H₃₉NO₁₃S + H]⁺.

3. Preparation of *S*-3-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-entahydroxyhexyl)amino)ethoxy)benzyl 2-methylpropanethioate hydrochloride (**14**);

Scheme 3



Preparation of *S*-3-(2-((*tert*-butoxycarbonyl)amino)ethoxy)benzyl 2-methylpropanethioate (12);

To a solution of compound **6** (2.60 g, 9.18 mmol) and Et₃N (3.75 mL, 27.5 mmol) in CH₂Cl₂ (50 mL) was added isobutyryl chloride (**11**, 1.45 mL, 13.8 mmol) at 0 °C dropwise and stirred at rt for 1 h. Water (20 mL) was added to the reaction mixture and extracted with CH₂Cl₂ (3 × 50 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄, filtered, concentrated and the residue purified by column chromatography to afford compound **12** (3.00 g, 93%) as an off-white solid: ¹H NMR (400 MHz, CD₃Cl) δ 7.19 (t, *J* = 7.7 Hz, 1H), 6.88 (dd, *J* = 7.6, 1.6 Hz, 1H), 6.82 (t, *J* = 2.3 Hz, 1H), 6.76 (dd, *J* = 8.2, 2.6 Hz, 1H), 4.98 (brs, 1H), 4.06 (s, 2H), 3.99 (t, *J* = 5.3 Hz, 2H), 3.55–3.45 (m, 2H), 2.26 (sep, *J* = 7.1 Hz, 1H), 1.45 (s, 9H), 1.20 (d, *J* = 7.1 Hz, 6H); ESI MS *m/z* 354 [M + H]⁺.

Preparation of *S*-3-(2-aminoethoxy)benzyl 2-methylpropanethioate hydrochloride (13);

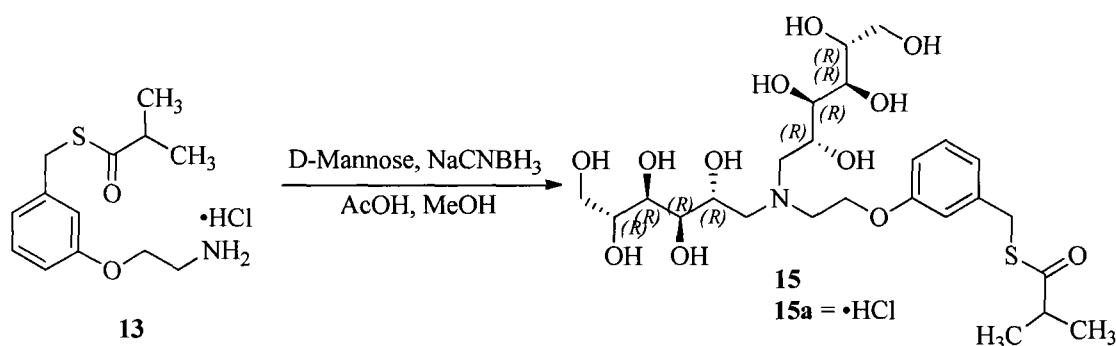
Compound **12** (3.00 g, 8.40 mmol) was dissolved in 4 N HCl in dioxane (30 mL) at room temperature and the solution was stirred for 1 h. After concentration, the residue was triturated with EtOAc to afford the hydrochloric acid salt **13** (2.25 g, 93%) as an off-white solid: ¹H NMR (400 MHz, CD₃OD) δ 7.23 (t, *J* = 7.5 Hz, 1H), 6.97–6.94 (m, 1H), 6.88 (dd, *J* = 7.6, 1.6 Hz, 1H), 6.92 (dd, *J* = 7.9, 2.1 Hz, 1H), 4.21 (t, *J* = 5.1 Hz, 2H), 4.08 (s, 2H), 3.35 (t, *J* = 5.4 Hz, 2H), 2.75 (sep, *J* = 7.1 Hz, 1H), 1.16 (d, *J* = 7.1 Hz, 6H); ESI MS *m/z* 254 [M + H]⁺.

Preparation of Preparation of *S*-3-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl 2-methylpropanethioate hydrochloride (14);

A solution of amine **13** (935 mg, 3.20 mmol) in methanol (50 mL) was charged with D-glucose (2.30 g, 12.7 mmol) and acetic acid (0.76 mL, 12.7 mmol) followed by sodium cyanoborohydride (800 mg, 12.7 mmol) and the resulting reaction mixture was heated and stirred at 50 °C for 4 h. Additional, D-glucose (0.58 g, 3.20 mmol) and acetic acid (0.19 mL, 3.20 mmol), and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting reaction mixture was heated stirred at 50 °C for 1 h. The solvent was removed under reduced pressure, and the residue purified by reverse-phase chromatography using a C18 Gold column. The pH of product fractions was adjusted to pH = 3 using 4 N HCl water, then were combined and the solvent removed by lyophilization to provide **14** (1.50 g, 76%) as an off-white solid: ¹H NMR (400 MHz, CD₃OD) δ 7.23 (t, *J* = 8.3 Hz, 1H), 6.97 (t, *J* = 1.9 Hz, 1H), 6.92 (td, *J* = 7.4, 2.4 Hz, 2H), 4.44–4.36 (m, 2H), 4.29–4.18 (m, 2H), 4.08 (s, 2H), 3.93–3.50 (m, 16H), 2.75 (sep, *J* = 7.2 Hz, 1H), 1.17 (d, *J* = 7.2 Hz, 6H); ¹H NMR (400 MHz, DMSO-*d*₆) δ 8.72 (brs, 1H), 7.24 (t, *J* = 7.5 Hz, 1H), 6.96–6.87 (m, 3H), 5.42–4.89 (m, 10H), 4.42–4.31 (m, 2H), 4.24–4.14 (m, 1H), 4.12–4.03 (m, 2H), 4.08 (s, 2H), 3.78–3.64 (m, 4H), 3.62–3.55 (m, 2H), 3.55–3.27 (m, 10H), 2.77 (sep, *J* = 7.0 Hz, 1H), 1.12 (d, *J* = 7.0 Hz, 6H); ESI MS *m/z* 582 [C₂₅H₄₃NO₁₂S + H].⁺

4. Preparation of *S*-3-(2-(bis((2*R*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl 2-methylpropanethioate hydrochloride (15);

Scheme 4

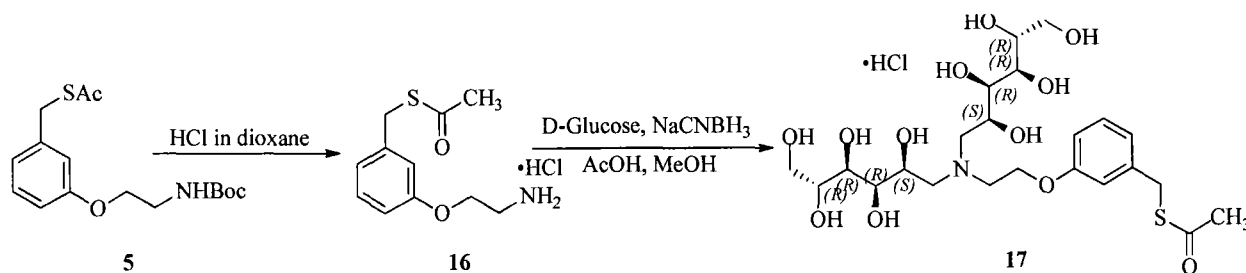


A solution of amine **13** (935 mg, 3.20 mmol) in methanol (50 mL) was charged with D-mannose (2.30 g, 12.7 mmol) and acetic acid (0.76 mL, 12.7 mmol) followed by sodium cyanoborohydride (800 mg, 12.7 mmol) and the resulting reaction mixture was heated and stirred at 50 °C for 4 h. Additional, D-mannose (0.58 g, 3.20 mmol), acetic acid (0.19 mL, 3.20 mmol), and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting reaction mixture was heated at 50 °C for another 1 h. After 1 h additional D-

mannose (0.58 g, 3.20 mmol), acetic acid (0.19 mL, 3.20 mmol), and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting mixture was heated at 50 °C for 1 h. The reaction mixture was cooled to rt, water was added (20 mL); the solvent was removed under reduced pressure, followed by additional water (20 mL). The precipitated solid was filtered and washed with water/methanol to get the born complex of the free base **15**. The free base was then acidified with 4 N HCl in water to make the salt then lyophilized to afford **15a** (1.25 g, 63%) as a off-white solid. ¹H NMR (400 MHz, CD₃OD) δ 7.22 (t, *J* = 7.5 Hz, 1H), 6.99–6.96 (m, 1H), 6.95–6.90 (m, 2H), 4.43–4.37 (m, 2H), 4.20–4.09 (m, 2H), 4.08 (s, 2H), 3.93–3.61 (m, 14H), 3.55–3.44 (m, 2H), 2.75 (sep, *J* = 7.2 Hz, 1H), 1.17 (d, *J* = 7.2 Hz, 6H); ¹H NMR (400 MHz, DMSO-*d*₆) δ 8.52 (brs, 1H), 7.24 (t, *J* = 8.4 Hz, 1H), 6.98–6.88 (m, 3H), 5.29–4.54 (m, 10H), 4.42–4.33 (m, 2H), 4.24–3.91 (m, 5H), 4.08 (s, 2H), 3.81–3.21 (m, 14H), 2.77 (sep, *J* = 7.0 Hz, 1H), 1.12 (d, *J* = 7.0 Hz, 6H); ESI MS *m/z* 582 [C₂₅H₄₃NO₁₂S + H]⁺.

5. Preparation of *S*-3-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl ethanethioate hydrochloride (17**);**

Scheme 5



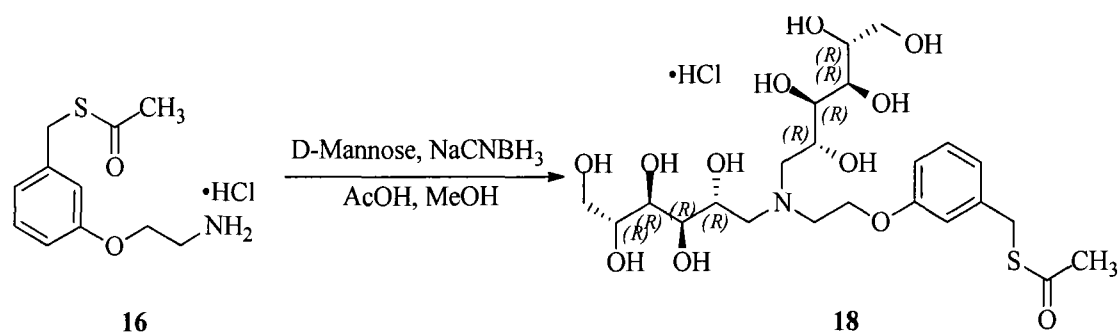
Preparation of *S*-3-(2-aminoethoxy)benzyl ethanethioate hydrochloride (16**);** Compound **5** (4.00 g, crude, 12.7 mmol) was dissolved in 4 N HCl in dioxane (40 mL) at room temperature and the solution was stirred for 1 h. After concentration, the residue was triturated with EtOAc then isolated by filtration to afford the hydrochloric acid salt **16** (2.60 g, 79%) as an off-white solid: ¹H NMR (400 MHz, CD₃OD) δ 7.23 (t, *J* = 7.9 Hz, 1H), 6.96–6.94 (m, 1H), 6.93 (dd, *J* = 7.9, 1.6 Hz, 1H), 6.88 (ddd, *J* = 8.4, 2.5, 1.1 Hz, 1H), 4.20 (t, *J* = 5.0 Hz, 2H), 4.09 (s, 2H), 3.35 (t, *J* = 5.0 Hz, 2H), 2.32 (s, 3H); ESI MS *m/z* 226 [M + H]⁺.

Preparation of *S*-3-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl ethanethioate hydrochloride (17**);**

A solution of amine **16** (835 mg, 3.20 mmol) in methanol (50 mL) was charged with D-glucose (2.30 g, 12.7 mmol) and acetic acid (0.76 mL, 12.7 mmol) followed by sodium cyanoborohydride (800 mg, 12.7 mmol) and the resulting reaction mixture was heated at 50 °C for 4 h. Additional, D-glucose (0.58 g, 3.20 mmol) acetic acid (0.19 mL, 3.20 mmol), and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting reaction mixture was heated at 50 °C for 1 h. The solvent was removed under reduced pressure and the residue purified by reverse-phase chromatography using a C18 Gold column. The pH of product fractions was adjusted to pH = 3 with 4 N HCl in water then combined and the solvent was removed by lyophilization to get **17** (1.10 g, 58%) as a white solid. ¹H NMR (400 MHz, CD₃OD) δ 7.24 (t, *J* = 7.8 Hz, 1H), 6.99–6.96 (m, 1H), 6.95–6.89 (m, 2H), 4.42–4.37 (m, 2H), 4.28–4.18 (m, 2H), 4.09 (s, 2H), 3.92–3.50 (m, 16H), 2.32 (s, 3H); ¹H NMR (400 MHz, DMSO-*d*₆) δ 8.66 (brs, 1H), 7.24 (t, *J* = 8.5 Hz, 1H), 6.96–6.87 (m, 3H), 5.89–5.16 (m, 2H), 4.63–4.15 (m, 10H), 4.13–4.01 (m, 3H), 4.09 (s, 2H), 3.78–3.66 (m, 4H), 3.63–3.55 (m, 2H), 3.54–3.26 (m, 10H), 2.35 (s, 3H); ESI MS *m/z* 554 [C₂₃H₃₉NO₁₂S + H].⁺

6. Preparation of *S*-3-(2-(bis((2*R*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl ethanethioate (18**);**

Scheme 6



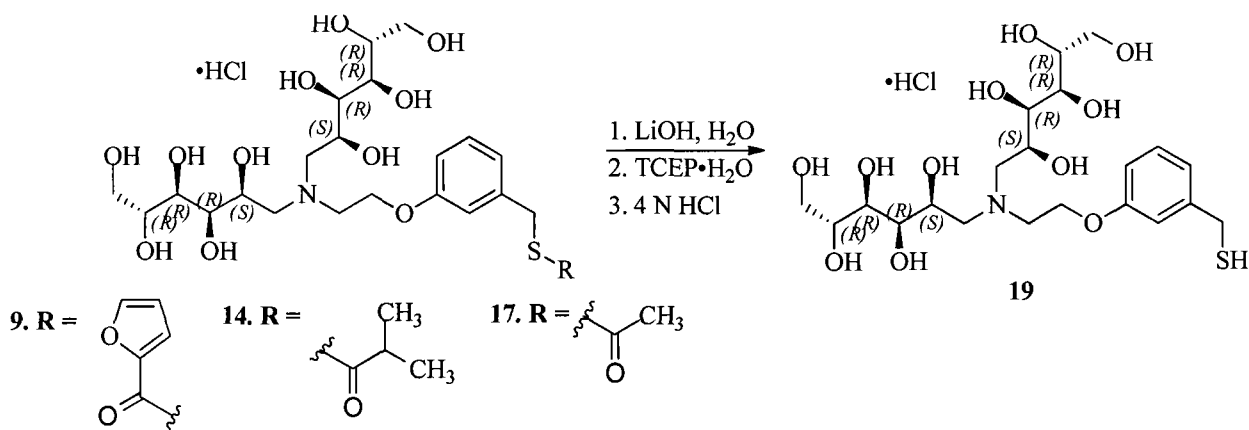
Preparation of Compound 18;

A solution of amine **16** (835 mg, 3.20 mmol) in methanol (50 mL) was charged with D-glucose (2.30 g, 12.7 mmol) and acetic acid (0.76 mL, 12.7 mmol) followed by sodium cyanoborohydride (800 mg, 12.7 mmol) and the resulting mixture was heated at 50 °C for 4 h. Additional, D-glucose (0.58 g, 3.20 mmol), acetic acid (0.19 mL, 3.20 mmol), and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting mixture heated at 50 °C for 1 h. A second equivalent of D-mannose (0.58 g, 3.20 mmol), acetic acid (0.19 mL, 3.20 mmol), and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting mixture was heated at 50 °C for 1 h. The reaction mixture was cooled to rt and water was

added; after solvent was removed under reduced pressure, more water was added and a solid precipitated out and was filtered washing with water/methanol to get the boron complex of the free base **18**. The free base complex was then acidified with 4 N HCl in water to make HCL salt and lyophilized to get **18** (90% pure by HPLC) as an off-white solid. The solid was further purified by reverse-phase chromatography using a C18 Gold column to get **18** (450 mg, 24%) as a white solid and an additional 1.00 g of **18**, <95% purity by HPLC, was isolated as well. ^1H NMR (400 MHz, CD_3OD) δ 7.22 (t, $J = 7.8$ Hz, 1H), 6.99–6.97 (m, 1H), 6.95–6.90 (m, 2H), 4.42–4.37 (m, 2H), 4.19–4.11 (m, 2H), 4.09 (s, 2H), 3.94–3.61 (m, 14H), 3.55–3.44 (m, 2H), 2.32 (s, 3H); ^1H NMR (400 MHz, $\text{DMSO}-d_6$) δ 8.42 (brs, 1H), 7.25 (t, $J = 7.9$ Hz, 1H), 6.93–6.86 (m, 3H), 5.71–5.57 (m, 1H), 5.54–5.42 (m, 1H), 4.92–4.15 (m, 11H), 4.09 (s, 2H), 4.05–3.87 (m, 3H), 3.77–3.21 (m, 14H), 2.35 (s, 3H); ESI MS m/z 554 $[\text{C}_{23}\text{H}_{39}\text{NO}_{12}\text{S} + \text{H}]^+$.

7. Preparation of (2*R*,2'*R*,3*R*,3'*R*,4*R*,4'*R*,5*S*,5'*S*)-6,6'-((2-(3-(mercaptomethyl)phenoxy)ethyl)azanediyl)bis(hexane-1,2,3,4,5-pentaol) hydrochloride (19**);**

Scheme 7

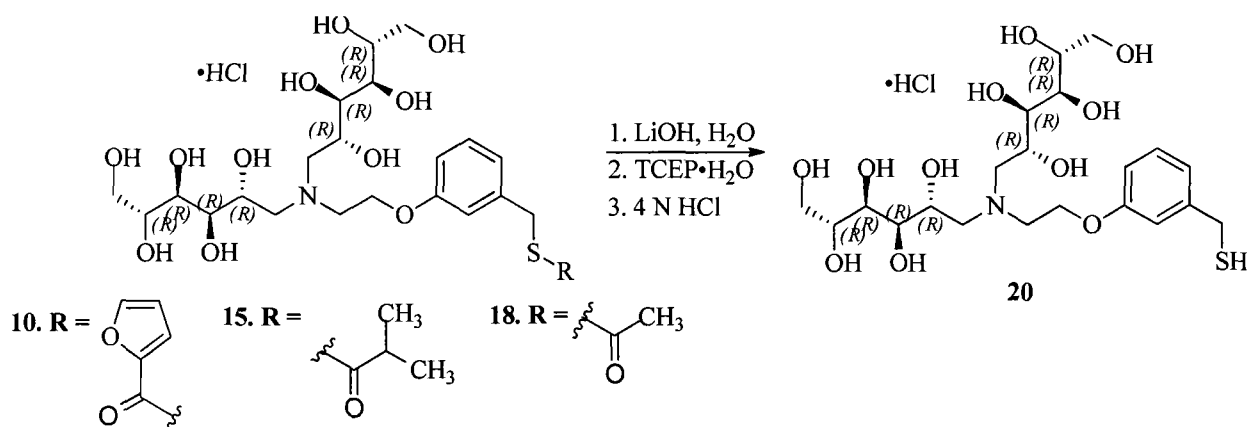


A solution of **9** (350 mg, 0.54 mmol) in water (15 mL) was charged with solid $\text{LiOH} \cdot \text{H}_2\text{O}$ (69 mg, 1.63 mmol) and the reaction mixture stirred at room temperature for 1 h. The mixture was charged with $\text{TCEP} \cdot \text{HCl}$ (154 mg, 0.54 mmol) and stirred for 1 h. The pH of the reaction was brought to pH = 2 by aqueous 4 N HCl and solvent was removed. Similarly, 335 mg (0.54 mmol) of **14** and 150 mg (0.25 mmol) of **17** was treated with $\text{LiOH} \cdot \text{H}_2\text{O}$, $\text{TCEP} \cdot \text{HCl}$ and after acidification with 4N HCl, combined with product from **9** and purified by reverse-phase column chromatography then lyophilized to afford 550 mg (75%) of pure compound

19 as a hygroscopic white solid: ^1H NMR (400 MHz, CD_3OD) δ 7.23 (t, $J = 7.8$ Hz, 1H), 7.05–7.01 (m, 1H), 6.98 (d, $J = 8.1$ Hz, 1H), 6.90 (dd, $J = 8.1, 2.4$ Hz, 1H), 4.40–4.37 (m, 2H), 4.30–4.17 (m, 2H), 3.96–3.48 (m, 18H); ^1H NMR (400 MHz, $\text{DMSO}-d_6$) δ 8.67 (brs, 1H), 7.24 (t, $J = 7.8$ Hz, 1H), 7.01–6.98 (m, 1H), 6.96 (d, $J = 8.0$ Hz, 1H), 6.87 (dd, $J = 8.0, 2.5$ Hz, 1H), 4.72–4.15 (m, 10H), 4.14–4.02 (m, 2H), 3.78–3.66 (m, 7H), 3.64–3.55 (m, 2H), 3.53–3.28 (m, 11H), 2.88 (t, $J = 7.7$ Hz, 1H); ESI MS m/z 512 [$\text{C}_{21}\text{H}_{37}\text{NO}_{11}\text{S} + \text{H}$].⁺

8. Preparation of (2*R*,2'*R*,3*R*,3'*R*,4*R*,4'*R*,5*R*,5'*R*)-6,6'-((2-(3-(mercaptomethyl)phenoxy)ethyl)azanediyl)bis(hexane-1,2,3,4,5-pentaol) hydrochloride (20**);**

Scheme 8

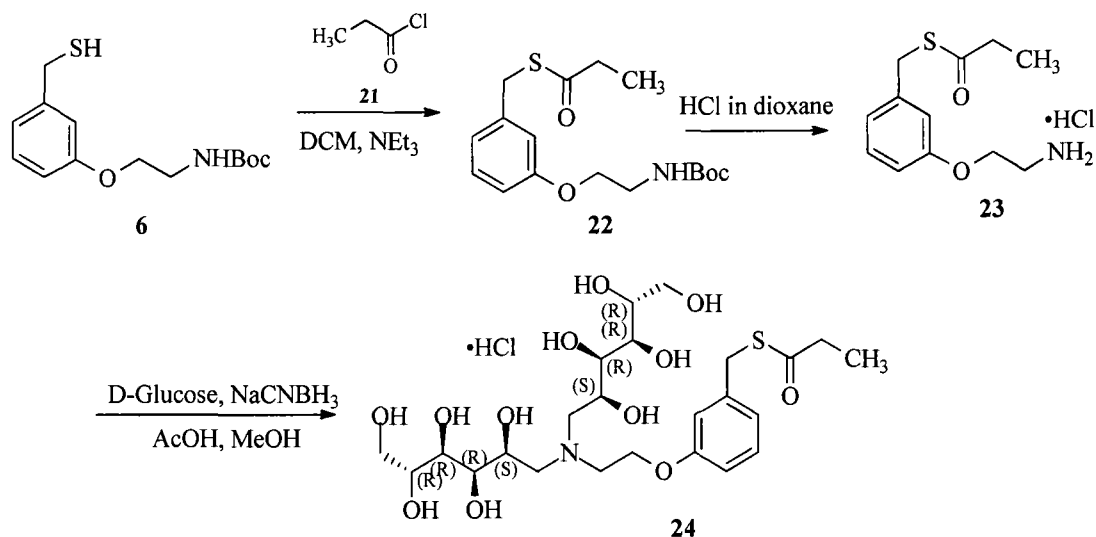


A solution of **10** (350 mg, 0.54 mmol) in water (15 mL) was charged with solid $\text{LiOH} \cdot \text{H}_2\text{O}$ (69 mg, 1.63 mmol) and the mixture stirred at room temperature for 1 h. The reaction mixture was charged with $\text{TCEP} \cdot \text{HCl}$ (30.0 mg, 0.10 mmol) and stirred for 1 h. The pH of above reaction mixture was brought to pH = 2 by aqueous 4 N HCl and solvent was removed. Similarly, 220 mg (0.35 mmol) of **15** and 1.00 g (1.70 mmol) of **18** was treated with $\text{LiOH} \cdot \text{H}_2\text{O}$, $\text{TCEP} \cdot \text{HCl}$ and after acidification with 4N HCl, combined with product derived from **10** and purified by reverse-phase column chromatography and lyophilized to afford 750 mg (53%) of pure compound **20** as a hygroscopic white solid: ^1H NMR (400 MHz, CD_3OD) δ 7.23 (t, $J = 7.9$ Hz, 1H), 7.04 (t, $J = 1.9$ Hz, 1H), 6.97 (d, $J = 7.9$ Hz, 1H), 6.91 (dd, $J = 8.1, 2.4$ Hz, 1H), 4.46–4.37 (m, 2H), 4.22–4.09 (m, 2H), 3.96–3.61 (m, 16H), 3.56–3.44 (m, 2H); ^1H NMR (400 MHz, $\text{DMSO}-d_6$) δ 8.54 (brs, 1H), 7.24 (t, $J = 7.9$ Hz, 1H), 7.01 (t, $J = 2.5$ Hz, 1H), 6.96 (d, $J = 7.9$ Hz, 1H), 6.88 (dd, $J = 7.9, 2.5$ Hz, 1H), 5.35–4.71 (m, 10H), 4.47–4.28

(m, 2H), 4.09–3.93 (m, 2H), 3.78–3.23 (m, 17H), 2.88 (t, $J = 7.7$ Hz, 1H); ESI MS m/z 512 $[\text{C}_{21}\text{H}_{37}\text{NO}_{11}\text{S} + \text{H}]^+$

9. Preparation of *S*-3-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl propanethioate hydrochloride (24);

Scheme 9



Preparation of *S*-3-(2-((*tert*-butoxycarbonyl)amino)ethoxy)benzyl propanethioate (22); To a solution of compound 6 (2.70 g, 9.54 mmol) and Et₃N (3.90 mL, 28.6 mmol) in CH₂Cl₂ (50 mL) was added propionyl chloride (21, 1.29 mL, 14.3 mmol) at 0 °C dropwise then stirred at rt for 1h. The solid was filtered and filtrate concentrated. Water (20 mL) was added to the reaction mixture and extracted with CH₂Cl₂ (3 × 50 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄, concentrated, and the residue purified by column chromatography to afford compound 22 (3.00 g, 93% over two steps) as an off-white solid: ¹H NMR (400 MHz, CD₃Cl) δ 7.19 (t, $J = 8.0$ Hz, 1H), 6.88 (dd, $J = 7.7, 1.3$ Hz, 1H), 6.82 (t, $J = 2.1$ Hz, 1H), 6.76 (dd, $J = 8.4, 2.4$ Hz, 1H), 4.98 (brs, 1H), 4.08 (s, 2H), 3.99 (t, $J = 5.1$ Hz, 2H), 3.56–3.465 (m, 2H), 2.59 (q, $J = 7.8$ Hz, 2H), 1.45 (s, 9H), 1.19 (t, $J = 7.9$ Hz, 3H); ESI MS m/z 340 $[\text{M} + \text{H}]^+$

Preparation of *S*-3-(2-aminoethoxy)benzyl propanethioate hydrochloride (23); Compound 22 (3.00 g, 8.84 mmol) was dissolved in 4 N HCl in dioxane (30 mL) at room temperature and the solution was stirred for 1 h. After concentration, the residue was triturated with EtOAc and isolation by filtration afforded the hydrochloric acid salt 23 (2.20 g, 91%) as an off-white solid: ¹H NMR (400 MHz, CD₃OD) δ 7.22 (t, $J = 8.0$ Hz, 1H), 6.95 (t, $J = 1.9$ Hz, 1H), 6.92 (d, $J = 7.6$ Hz, 1H), 6.88 (ddd, $J = 8.2, 2.5, 0.7$ Hz, 1H), 4.21 (t, $J = 5.1$ Hz, 2H),

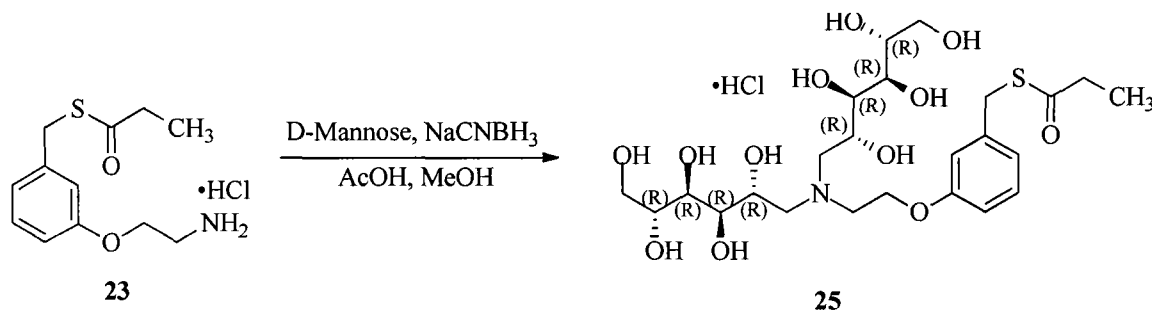
4.09 (s, 2H), 3.35 (t, $J = 5.1$ Hz, 2H), 2.59 (q, $J = 7.4$ Hz, 2H), 1.44 (t, $J = 7.1$ Hz, 3H); ESI MS m/z 240 $[M + H]^+$

Preparation of *S*-3-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl propanethioate hydrochloride (24);

A solution of amine **23** (880 mg, 3.20 mmol) in methanol (50 mL) was charged with D-glucose (2.30 g, 12.7 mmol) and acetic acid (0.76 mL, 12.7 mmol) followed by sodium cyanoborohydride (800 mg, 12.7 mmol) and the resulting mixture was heated and stirred at 50 °C for 4 h. Additional, D-glucose (0.58 g, 3.20 mmol), acetic acid (0.19 mL, 3.20 mmol), and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting mixture was heated at 50 °C for 1 h. The solvent was removed under reduced pressure and the residue purified by reverse-phase chromatography using a C18 Gold column. The pH of product fractions was adjusted to pH = 3 with 4 N HCl in water then combined and the was removed by lyophilization to provide **24** (1.67 g, 88%) as an off-white solid. ^1H NMR (400 MHz, CD_3OD) δ 7.22 (t, $J = 8.5$ Hz, 1H), 6.99–6.96 (m, 1H), 6.96–6.89 (m, 2H), 4.43–4.37 (m, 2H), 4.29–4.17 (m, 2H), 4.10 (s, 2H), 3.93–3.51 (m, 16H), 2.59 (q, $J = 7.9$ Hz, 2H), 1.15 (t, $J = 7.9$ Hz, 3H); ^1H NMR (400 MHz, $\text{DMSO}-d_6$) δ 8.74 (brs, 1H), 7.24 (t, $J = 7.8$ Hz, 1H), 6.96–6.85 (m, 3H), 4.83 (brs, 7H), 4.44–4.31 (m, 2H), 4.24–4.14 (m, 1H), 4.13–4.07 (m, 4H), 4.09 (s, 2H), 3.78–3.25 (m, 16H), 2.61 (q, $J = 7.8$ Hz, 2H), 1.07 (t, $J = 7.8$ Hz, 3H); ESI MS m/z 568 $[\text{C}_{24}\text{H}_{41}\text{NO}_{12}\text{S} + \text{H}]^+$

10. Preparation of *S*-3-(2-(bis((2*R*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl propanethioate hydrochloride (25);

Scheme 10

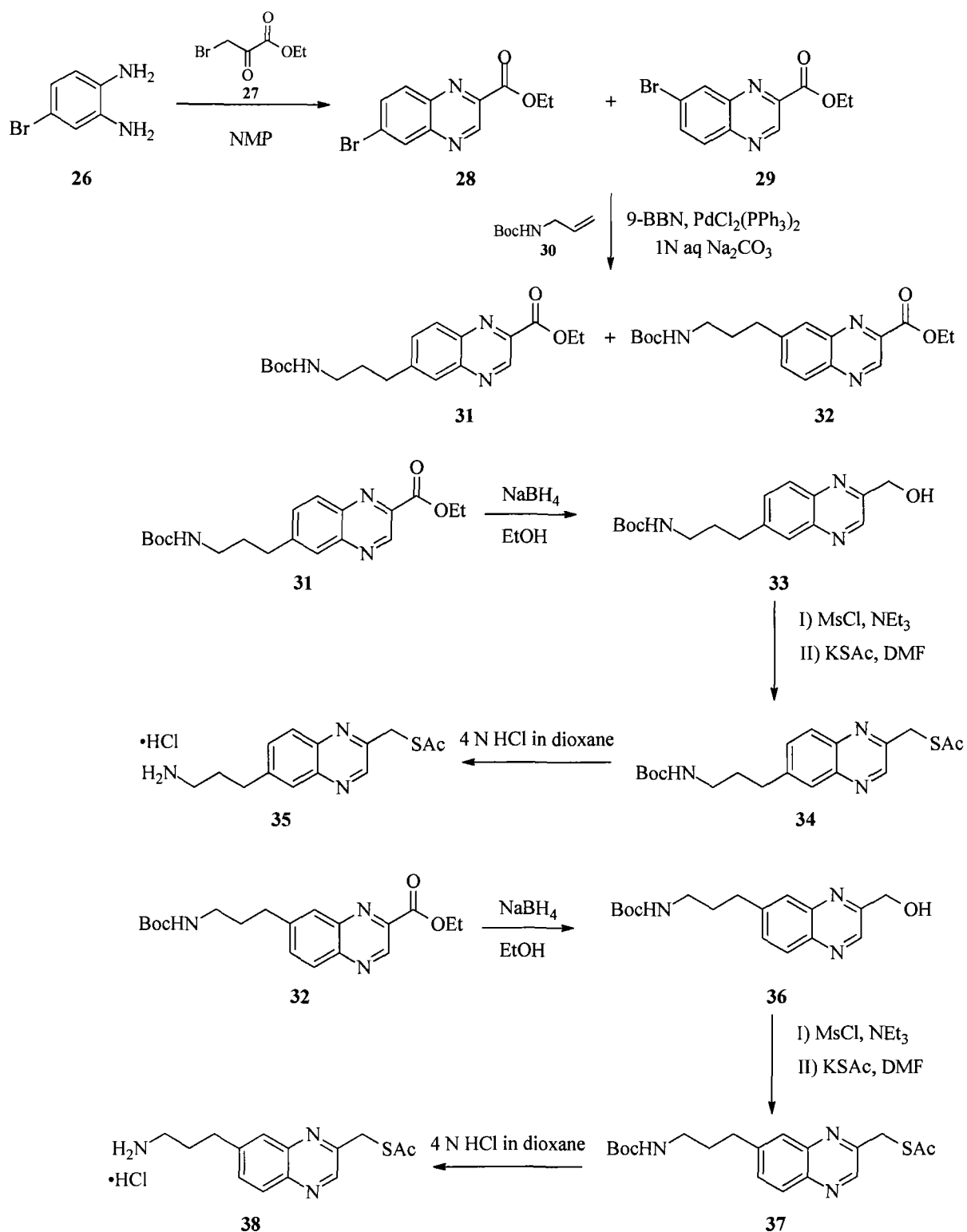


A solution of amine **23** (880 mg, 3.20 mmol) in methanol (50 mL) was charged with D-mannose (2.30 g, 12.7 mmol) and acetic acid (0.76 mL, 12.7 mmol) followed by sodium cyanoborohydride (800 mg, 12.7 mmol) and the resulting mixture was heated and stirred at 50 °C for 4 h. Additional, D-mannose (0.58 g, 3.20 mmol), acetic acid (0.19 mL, 3.20 mmol),

and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting reaction mixture was heated at 50 °C for 1 h. An additional portion of D-mannose (0.58 g, 3.20 mmol), acetic acid (0.19 mL, 3.20 mmol), and sodium cyanoborohydride (200 mg, 3.20 mmol) were added and the resulting mixture was heated at 50 °C for 1 h. The reaction mixture was cooled to rt and water was added (20 mL); after solvent was removed under reduced pressure, additional water (20 mL) was added and the resulting solid was filtered, washed with water/methanol to afford the free base of **25**. The free base was then acidified with 4 N HCl in water to make HCL salt and lyophilized to get **25** (1.30 g, 67%) as an off-white solid: ¹H NMR (400 MHz, CD₃OD) δ 7.25 (t, *J* = 7.8 Hz, 1H), 7.00–6.96 (m, 1H), 6.96–6.90 (m, 2H), 4.44–4.11 (m, 2H), 4.22–4.11 (m, 2H), 4.10 (s, 2H), 3.94–3.61 (m, 14H), 3.57–3.44 (m, 2H), 2.59 (q, *J* = 7.9 Hz, 2H), 1.15 (t, *J* = 7.9 Hz, 3H); ¹H NMR (400 MHz, DMSO-*d*₆) δ 8.74 (brs, 1H), 7.24 (t, *J* = 8.1 Hz, 1H), 6.98–6.88 (m, 3H), 5.02–4.46 (m, 5H), 4.45–4.30 (m, 4H), 4.23–3.89 (m, 8H), 3.84–3.19 (m, 16H), 2.61 (q, *J* = 7.8 Hz, 2H), 1.08 (t, *J* = 7.8 Hz, 3H); ESI MS *m/z* 568 [C₂₄H₄₁NO₁₂S + H].⁺

11. Preparation of *S*-((6-(3-aminopropyl)quinoxalin-2-yl)methyl) ethanethioate hydrochloride (35) and Preparation of *S*-((7-(3-aminopropyl)quinoxalin-2-yl)methyl) ethanethioate hydrochloride (38);

Scheme 11



Preparation of ethyl 6-bromoquinoxaline-2-carboxylate (28) and ethyl 7-bromoquinoxaline-2-carboxylate; (29)

To a stirred solution of 4-bromo-o-phenylenediamine (10.0 g, 54.05 mmol) in 1-methyl-2-pyrrolidinone (50 mL) was added dropwise ethyl bromopyruvate **27** (20.9 g, 108.1 mmol) at

room temperature under nitrogen. After 20 hours, the reaction mixture was partitioned between water (100 mL) and ethyl acetate (100 mL). The organic phase was separated and the aqueous phase extracted with ethyl acetate (2×100 mL). The combined organic extracts were, washed with water (2×50 mL), dried over magnesium sulfate, filtered, and the filtrate was concentrated. The crude product was purified by flash chromatography over silica gel to afford a 60:40% mixture of regioisomers **28** and **29** (6.50 g, 43%) which was characterized by HPLC and LC-MS analysis and directly used for next step. ESI-LCMS m/z 282 ($M+H$)⁺.

Preparation of ethyl 6-(3-((tert-butoxycarbonyl)amino)propyl)quinoxaline-2-carboxylate (31) and ethyl 7-(3-((tert-butoxycarbonyl)amino)propyl)quinoxaline-2-carboxylate; (32)

To a solution of compound **30** (3.64 g, 23.21 mmol) in anhydrous THF (300 mL) was added 9-BBN (0.5 M in THF, 116 mL, 58.05 mmol) under argon. After the reaction mixture was stirred for 2 h at room temperature, compound **28** and **29** (6.50 g, 23.2 mmol), Pd(PPh₃)₂Cl₂ (814 mg, 1.16 mmol), and 2 N aq Na₂CO₃ (15 mL) were added at room temperature. The resulting mixture was stirred for 1 h. After solvent removed; the residue was partitioned between EtOAc (200 mL) and water (200 mL). The aqueous layer was separated and extracted with EtOAc (2×200 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄ and concentrated under vacuum. The crude product was purified by silica-gel column chromatography followed by Chiral HPLC (OD) 10% ethanol in heptane as eluent to get 5.10 g, 61% (2.50 g of **32** and 1.75 g of **31**), which were characterized by ¹H NMR and LC-MS analysis.

(31) ¹H NMR (CDCl₃, 300 MHz): δ 9.50 (s, 1H), 8.22 (d, $J = 8.8$ Hz, 1H), 7.95 (br s, 1H), 7.72–7.68 (m, 1H), 4.62–4.55 (m, 3H), 3.28–3.21 (m, 2H), 2.93 (t, $J = 7.4$ Hz, 2H), 2.02–1.91 (m, 2H), 1.50 (t, $J = 7.2$ Hz, 3H), 1.44 (s, 9H). ESI-LCMS m/z 360 ($M+H$)⁺.

(32) ¹H NMR (CDCl₃, 300 MHz): δ 9.48 (s, 1H), 8.05 (d, $J = 8.8$ Hz, 2H), 7.76–7.72 (m, 1H), 4.62–4.53 (m, 3H), 3.24–3.17 (m, 2H), 2.92 (t, $J = 7.6$ Hz, 2H), 2.05–1.91 (m, 2H), 1.50 (t, $J = 7.2$ Hz, 3H), 1.44 (s, 9H). ESI-LCMS m/z 360 ($M+H$)⁺.

Preparation of tert-butyl (3-(2-(hydroxymethyl)quinoxalin-6-yl)propyl)carbamate; (33)

A solution of compound **31** (1.75 g, 4.87 mmol) in EtOH (100 mL) was charged with sodium borohydride (926 mg, 24.3 mmol) at 0 °C. The resulting reaction mixture was stirred at rt for 3 h and the residue was partitioned between EtOAc (100 mL) and water (100 mL). The aqueous layer was separated and extracted with EtOAc (2×100 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄, filtered, and concentrated under vacuum. The crude product was purified by column chromatography to afford compound **33** (1.10 g, 71%) as a brown liquid used immediately for next step; ESI MS m/z 318 [$M + H$]⁺.

Preparation of *S*-((6-(3-((*tert*-butoxycarbonyl)amino)propyl)quinoxalin-2-yl)methyl)ethanethioate; (34)

A solution of **33** (1.10 g, 3.47 mmol) in CH₂Cl₂ (100 mL) was charged with Et₃N (0.6 mL, 4.16 mmol) followed by methane sulfonyl chloride (490 mg, 4.16 mmol) at 0 °C then stirred at room temperature for 2 h. The reaction mixture was diluted with water (100 mL) and extracted with CH₂Cl₂ (3 × 150 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄, and concentrated to afford the mesylated product (1.40 g, crude) as yellow oil, which was directly used for the next step without further purification: ESI MS *m/z* 396 [M + H].⁺

Crude mesylate (1.40 g, 3.54 mmol) in DMF (10 mL) was charged with KSAc (1.02 g, 8.85 mmol) and stirred at room temperature for 2 h. The solvent was removed and the residue partitioned between water (100 mL) and EtOAc (100 mL). The EtOAc layer was separated and the aqueous layer was extracted with EtOAc (2 × 100 mL). The combined organic layers were concentrated and the residue was purified by column chromatography to afford compound **34** (700 mg, 54% over two steps) as a yellow solid: ¹H NMR (400 MHz, CDCl₃) δ 8.84 (s, 1H), 7.95 (d, *J* = 8.6 Hz, 1H), 7.86 (br s, 1H), 7.61–7.59 (m, 1H), 4.57 br s, 1H), 4.44 (s, 2H), 3.23–3.16 (m, 2H), 2.88 (t, *J* = 7.4 Hz, 2H), 2.40 (s, 3H), 1.96–1.89 (m, 2H), 1.44 (s, 9H); ESI MS *m/z* 376 [M + H].⁺

Preparation of *S*-((6-(3-aminopropyl)quinoxalin-2-yl)methyl)ethanethioate hydrochloride; (35)

Compound **34** (500 mg, 1.33 mmol) was dissolved in DCM (5 mL) followed by the addition of 4 N HCl in dioxane (5 mL) drop wise at room temperature, then the solution was stirred at room temperature for 2 h. After removal of the solvent, the residue triturated with EtOAc/Hexane then isolated by filtration to afford hydrochloric acid salt **35** (300 mg, 83%) as an off-white solid: ¹H NMR (300 MHz, CD₃OD) δ 8.87 (s, 1H), 8.01–7.91 (m, 2H), 7.76–7.73 (m, 1H), 4.46 (s, 2H), 3.03–2.96 (m, 4H), 2.38 (s, 3H), 2.14–2.07 (m, 2H); ¹H NMR (300 MHz, DMSO-*d*₆) δ 8.91 (s, 1H), 7.99–7.91 (m, 5H), 7.77–7.71 (m, 1H), 4.47 (s, 2H), 2.95–2.77 (m, 4H), 2.39 (s, 3H), 2.05–1.92 (m, 2H); ESI MS *m/z* 276 [M + H].⁺

Preparation of *tert*-butyl (3-(3-(hydroxymethyl)quinoxalin-6-yl)propyl)carbamate; (36)

A solution of compound **32** (1.15 g, 3.20 mmol) in EtOH (100 mL) was charged with sodium borohydride (608 mg, 16.0 mmol) at 0 °C. The resulting reaction mixture was stirred at rt for 3 h and the residue was partitioned between EtOAc (100 mL) and water (100 mL). The aqueous layer was separated and extracted with EtOAc (2 × 100 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄ and concentrated under vacuum. The

crude product was purified by column chromatography to afford compound **36** (800 mg, 79%) as a brown liquid used immediately for next step; ESI MS m/z 318 $[M + H]^+$

Preparation of (7-(3-((*tert*-butoxycarbonyl) amino) propyl)quinoxalin-2-yl)methyl methanesulfonate;

A solution of **36** (800 mg, 2.52 mmol) in CH_2Cl_2 (100 mL) was charged with Et_3N (0.44 mL, 3.02 mmol) followed by methane sulfonyl chloride (356 mg, 3.02 mmol) at 0 °C then stirred at room temperature for 2 h. The reaction mixture was diluted with water (100 mL) and extracted with CH_2Cl_2 (3×150 mL). The combined organic extracts were washed with brine, dried over Na_2SO_4 , and concentrated to afford the mesylated product (680 mg, 68% crude) as yellow oil, which was directly used for the next step without further purification: ESI MS m/z 396 $[M + H]^+$

Preparation of *S*-((7-(3-((*tert*-butoxycarbonyl)amino)propyl)quinoxalin-2-yl)methyl) ethanethioate; (37**)**

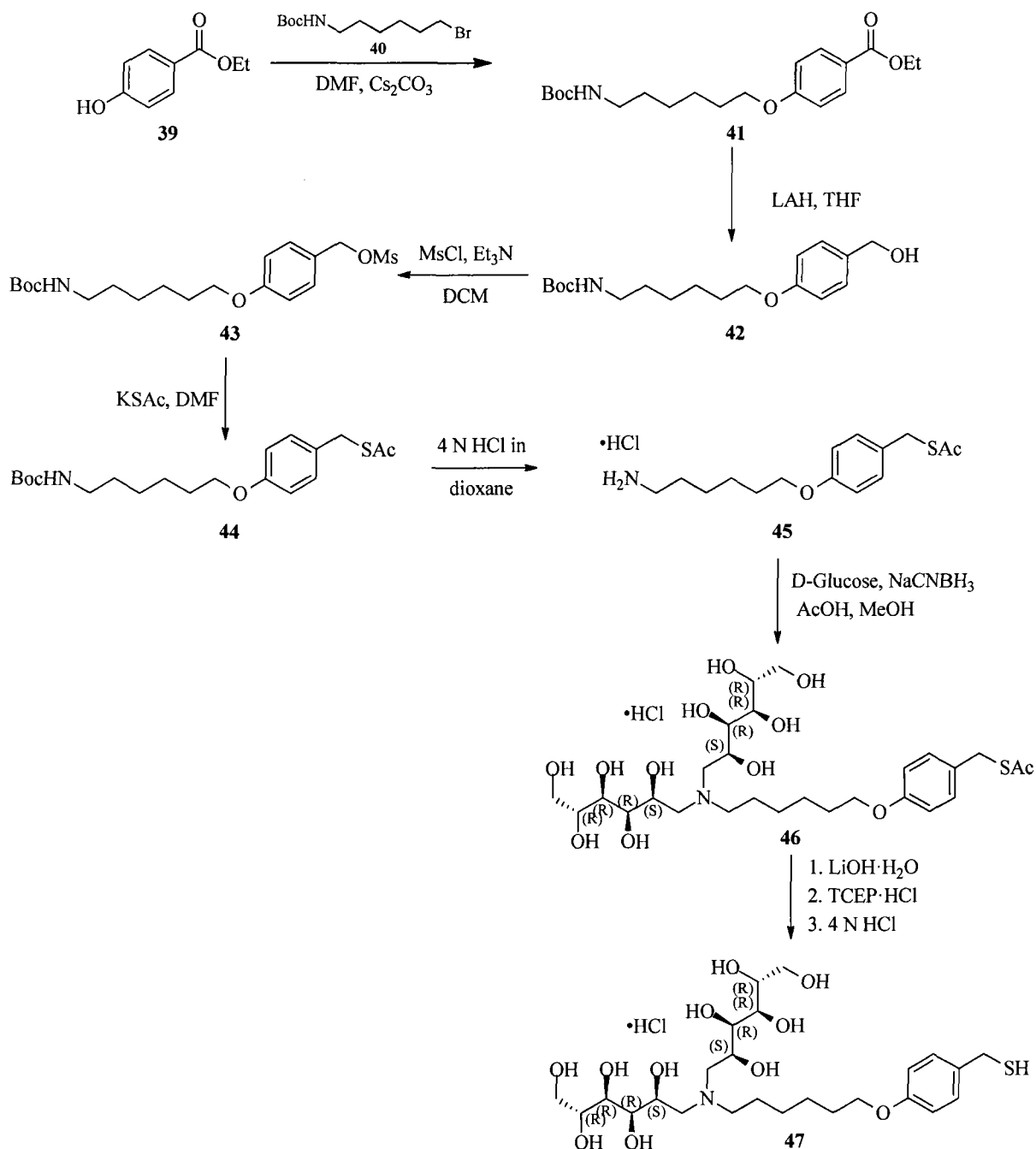
The crude product **36** (680 mg, 1.72 mmol, crude) in DMF (5 mL) was charged with KSAC (490 mg, 4.30 mmol) and stirred at room temperature for 2 h. The solvent was removed and the residue was partitioned between water (100 mL) and EtOAc (100 mL). The EtOAc layer was separated and the aqueous layer was extracted with EtOAc (2×100 mL). The combined organic layers were concentrated and the residue was purified by column chromatography to afford compound **37** (420 mg, 66%) as a yellow solid; ESI MS m/z 376 $[M + H]^+$

Preparation of *S*-((7-(3-aminopropyl)quinoxalin-2-yl)methyl) ethanethioate hydrochloride; (38**)**

Compound **37** (150 mg, 0.4 mmol) was dissolved in DCM (5 mL) followed by the addition of 4 N HCl in dioxane (5 mL) drop wise at room temperature, and the solution was stirred at same temperature for 2 h. After removal of the solvent, the residue washed with EtOAc/Hexane then isolated by filtration to afford hydrochloric acid salt **38** (66 mg, 61%) as an off-white solid: 1H NMR (300 MHz, CD_3OD) δ 8.85 (s, 1H), 8.06–7.99 (m, 1H), 7.88 (br s, 1H), 7.74–7.71 (m, 1H), 4.47 (s, 2H), 3.03–2.96 (m, 4H), 2.38 (s, 3H), 2.15–2.07 (m, 2H); 1H NMR (300 MHz, $DMSO-d_6$) δ 8.89 (s, 1H), 8.03 (d, $J = 8.4$ Hz, 1H), 7.96–7.81 (m, 4H), 7.73–7.77 (m, 1H), 4.47 (s, 2H), 2.92 (t, $J = 7.8$ Hz, 2H), 2.85–2.78 (m, 2H), 2.38 (s, 3H), 2.04–1.93 (m, 2H); ESI MS m/z 276 $[M + H]^+$

12. Preparation of *S*-4-((6-aminohexyl)oxy)benzyl ethanethioate hydrochloride (45**) and (2*R*,2'*R*,3*R*,3'*R*,4*R*,4'*R*,5*S*,5'*S*)-6,6'-((6-(4-(mercaptomethyl) phenoxy)hexyl) azanediyl)bis(hexane-1,2,3,4,5-pentaol) hydrochloride (**47**);**

Scheme 12

**Preparation of ethyl 4-((6-((tert-butoxycarbonyl)amino)hexyl)oxy)benzoate (**41**);**

A solution of compound **39** (3.00 g, 18.0 mmol) in DMF (80 mL) was charged with Cs_2CO_3 (11.7 g, 36.1 mmol) and stirred at room temperature for 5 min. The above reaction mixture was charged with compound **40** (10.1 g, 36.1 mmol) and the reaction mixture was stirred at room temperature for 20 h. The reaction mixture was diluted with water (100 mL) and extracted with EtOAc (3×100 mL). The combined organic layers were concentrated and the

residue purified by column chromatography to afford compound **41** (4.65 g, 70%) as a white gum which was directly used for next step; ESI MS m/z 366 $[M + H]^+$.

Preparation of *tert*-butyl (6-(4-(hydroxymethyl)phenoxy)hexyl)carbamate (42); A solution of compound **41** (4.60 g, 12.6 mmol) in THF (100 mL) was charged with lithium aluminum hydride (515 mg, 15.1 mmol) portion wise at 0 °C. The resulting reaction mixture was stirred at 0 °C for 1 h and quenched with ice-cold water at 0 °C. The reaction mixture was diluted with EtOAc (200 mL) and filtered through a Celite pad, and the Celite pad was washed with EtOAc (2 × 200 mL). The filtrate was concentrated under vacuum and it was purified by column chromatography to afford compound **42** (3.10 g, 76%) as a gummy solid which was directly used for next step; ESI MS m/z 324 $[M + H]^+$.

Preparation of 4-((6-((*tert*-butoxycarbonyl)amino)hexyl)oxy)benzyl methanesulfonate (43);

A solution of **42** (3.10 g, 9.59 mmol) in CH_2Cl_2 (100 mL) was charged with Et_3N (1.66 mL, 11.5 mmol) followed by methanesulfonyl chloride (1.35 g, 11.5 mmol) at 0 °C then stirred at room temperature for 2 h. The reaction mixture was diluted with water (100 mL) and extracted with CH_2Cl_2 (3 × 150 mL). The combined organic extracts were washed with brine, dried over Na_2SO_4 , and concentrated to afford the mesylated product **43** (3.40 g, 89%) as yellow oil, which was directly used for the next step without further purification: ESI MS m/z 401 $[M + H]^+$.

Preparation of *S*-4-((6-((*tert*-butoxycarbonyl)amino)hexyl)oxy)benzyl ethanethioate (44);

The above product **43** (3.40 g, 8.47 mmol) in DMF (100 mL) was charged with KSAc (2.41 g, 21.1 mmol) and stirred at room temperature for 2 h. The solvent was removed and the residue was partitioned between water (100 mL) and EtOAc (100 mL). The EtOAc layer was separated and the aqueous layer was extracted with EtOAc (2 × 100 mL). The combined organic layers were concentrated and the residue was purified by column chromatography to afford compound **44** (2.80 g, 87%) as a yellow solid: 1H NMR (400 MHz, $CDCl_3$) δ 7.18 (d, J = 8.6 Hz, 2H), 6.80 (d, J = 8.6 Hz, 2H), 4.49 (br s, 1H), 4.07 (s, 2H), 3.91 (t, J = 6.4 Hz, 2H), 3.15–3.07 (m, 2H), 2.33 (s, 3H), 1.77–1.72 (m, 2H), 1.51–1.34 (m, 15H); ESI MS m/z 381 $[M + H]^+$.

Preparation of *S*-4-((6-aminohexyl)oxy)benzyl ethanethioate hydrochloride (45);

Compound **44** (2.80 g, 7.34 mmol) was dissolved in 4 N HCl in dioxane (20 mL) at room temperature then the solution was stirred for 1 h. After removal of the solvent, the residue was triturated with EtOAc then filtered to afford the hydrochloric acid salt **45** (1.80 g, 87%) as a hygroscopic off-white solid: 1H NMR (300 MHz, CD_3OD) δ 7.17 (d, J = 8.8, 2H), 6.80

(d, $J = 8.8$, 2H), 4.05 (s, 2H), 3.96 (t, $J = 8.8$, 6.2, 2H), 2.92 (t, $J = 7.4$, 2H), 2.30 (s, 3H), 1.83–1.63 (m, 4H), 1.59–1.43 (m, 4H), ^1H NMR 300 MHz (DMSO- d_6): δ 7.88 (br s, 3H), 7.19 (d, $J = 8.8$, 2H), 6.84 (d, $J = 8.8$, 2H), 4.04 (s, 2H), 3.93 (t, $J = 6.4$, 2H), 2.75 (br s, 2H), 2.34 (s, 3H), 1.73–1.51 (m, 4H), 1.42–1.33 (m, 4H); ESI MS m/z 282 $[\text{M} + \text{H}]^+$.

Preparation *S-4-((6-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl) amino)hexyl) oxy) benzyl ethanethioate hydrochloride (46);*

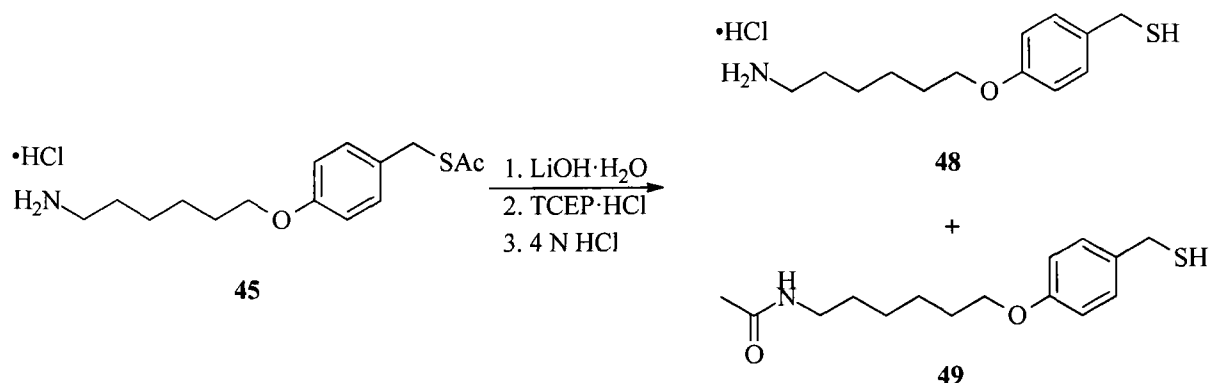
A solution of amine **45** (500 mg, 1.78 mmol) in methanol (50 mL) was charged with D-glucose (960 mg, 5.33 mmol) and acetic acid (0.32 mL, 5.33 mmol) followed by sodium cyanoborohydride (335 mg, 5.33 mmol) and the resulting mixture was stirred at room temperature for 16 h. Additional D-glucose (640 mg, 3.56 mmol), AcOH (0.21 mL, 3.56 mmol), and sodium cyanoborohydride (223 mg, 3.56 mmol) were charged and the mixture stirred for 24 h at room temperature. Further D-glucose (960 mg, 5.33 mmol), AcOH (0.32 mL, 5.33 mmol), and sodium cyanoborohydride (335 mg, 5.33 mmol) were charged and the mixture was stirred for 24 h at room temperature. After the solvent was removed the reaction mixture neutralized with NaHCO₃ solution and purified by reverse phase chromatography to afford pure **46** (710 mg, 66%) as a white solid.

Preparation *(2*R*,2'*R*,3*R*,3'*R*,4*R*,4'*R*,5*S*,5'*S*)-6,6'-((6-(4-(mercaptomethyl) phenoxy)hexyl) azanediyl)bis(hexane-1,2,3,4,5-pentaol) hydrochloride (47);*

A solution of compound **46** (710 mg, 1.16 mmol) in water (20 mL) was charged with solid LiOH·H₂O (195 mg, 4.66 mmol), and the reaction mixture was stirred for 1 h at room temperature, after that solid TCEP·HCl (165 mg, 0.58 mmol) was added and the reaction mixture was stirred at room temperature for 2 h. The reaction was acidified with 4 N HCl and the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **47** (420 mg, 64%) as a colorless gummy solid: ^1H NMR (300 MHz, CD₃OD) δ 7.22 (d, $J = 8.6$, 2H), 6.83 (d, $J = 8.6$, 2H), 4.16 (br s, 2H), 3.98–3.96 (m, 2H), 3.83–3.72 (m, 4H), 3.71–3.59 (m, 8H), 3.51–3.36 (m, 5H), 1.90–1.72 (m, 4H), 1.64–1.43 (m, 4H); ^1H NMR 300 MHz (DMSO- d_6): δ 8.74 (br s, 1H), 7.22 (d, $J = 8.6$, 2H), 6.84 (d, $J = 8.6$, 2H), 5.45–5.40 (m, 2H), 4.79–4.45 (m, 8H), 4.00–3.91 (m, 4H), 3.70–3.64 (m, 4H), 3.62–3.56 (m, 2H), 3.51–3.38 (m, 7H), 3.26–3.14 (m, 5H), 2.73 (t, $J = 7.4$, 1H), 1.77–1.64 (m, 4H), 1.49–1.29 (m, 4H); ESI MS m/z 568 $[\text{M} + \text{H}]^+$.

13. Preparation of *Compound 48 and 49*;

Scheme 13

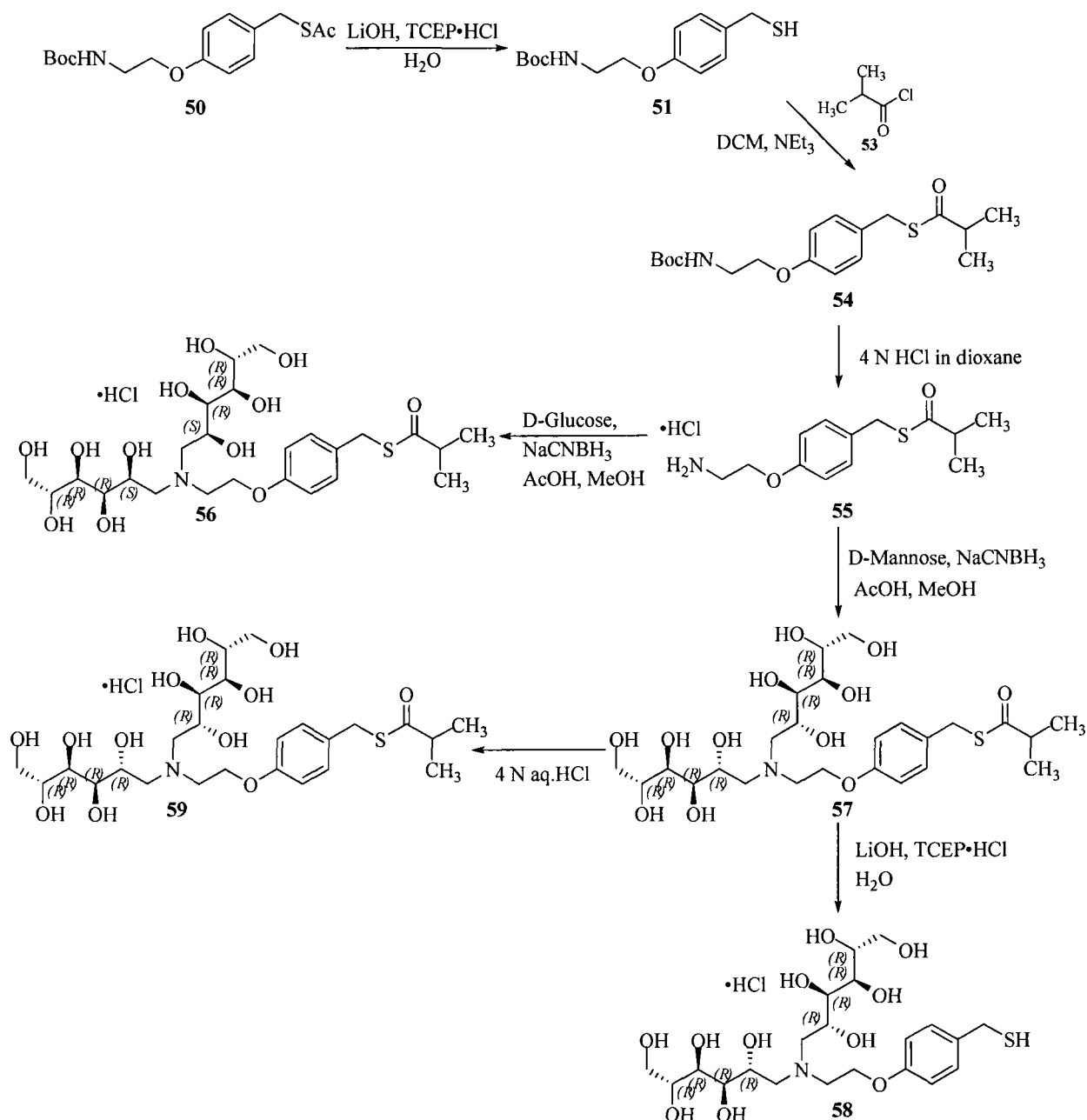
Preparation of *Compound 48: and 49*

A solution of **45** (200 mg, 0.71 mmol) in water (50 mL), was charged with solid LiOH·H₂O (120 mg, 2.84 mmol), and stirred for 1 h at room temperature, followed by the addition of TCEP·HCl (406 mg, 1.42 mmol) and the reaction mixture was stirred at room temperature for 1 h. After completion of the reaction it was acidified with 1 N HCl and purified by reverse phase chromatography to afford compound **48** (80 mg, 47%) and **49** (50 mg, 25%) as an off-white solid:

¹H NMR (300 MHz, CD₃OD) δ 7.22 (d, *J* = 8.6, 2H), 6.82 (d, *J* = 8.6, 2H), 3.96 (t, *J* = 6.2, 2H), 3.67 (br s, 2H), 2.92 (t, *J* = 7.4, 2H), 1.84–1.63 (m, 4H), 1.59–1.46 (m, 4H); ¹H NMR 300 MHz (DMSO-*d*₆): δ 7.85 (br s, 3H), 7.22 (d, *J* = 8.6, 2H), 6.85 (d, *J* = 8.6, 2H), 3.93 (t, *J* = 6.6, 2H), 3.67 (d, *J* = 7.2, 2H), 2.78–2.71 (m, 3H), 1.74–1.51 (m, 4H), 1.46–1.34 (m, 4H). ESI MS *m/z* 240 [M + H].⁺

(**49**): ¹H NMR (300 MHz, CD₃OD) δ 7.21 (d, *J* = 8.6, 2H), 6.82 (d, *J* = 8.6, 2H), 3.94 (t, *J* = 6.4, 2H), 3.67 (br s, 2H), 3.16 (t, *J* = 6.6, 2H), 1.91 (s, 3H), 1.78–1.71 (m, 2H), 1.58–1.36 (m, 6H); ¹H NMR 300 MHz (DMSO-*d*₆): δ 7.75 (br s, 1H), 7.21 (d, *J* = 8.6, 2H), 6.84 (d, *J* = 8.6, 2H), 3.92 (d, *J* = 6.6, 2H), 3.67 (d, *J* = 7.6, 2H), 3.04–2.97 (m, 3H), 2.72 (t, *J* = 7.2, 1H), 1.77 (s, 3H), 1.71–1.66 (m, 2H), 1.41–1.34 (m, 6H). ESI MS *m/z* 282 [M + H].⁺

14. Preparation of *S*-4-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl) amino)ethoxy) benzyl 2-methylpropanethioate hydrochloride (**56**); *S*-4-(2-(bis((2*R*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl) amino)ethoxy) benzyl 2-methylpropanethioate hydrochloride (**59**); and (2*R*,2'*R*,3*R*,3'*R*,4*R*,4'*R*,5*R*,5'*R*)-6,6'-((2-(4-(mercaptomethyl) phenoxy) ethyl) azanediyl) bis (hexane-1,2,3,4,5-pentaol) hydrochloride (**58**);

Scheme 14

Preparation of *tert*-butyl (2-(4-(mercaptomethyl)phenoxy)ethyl)carbamate (51**);**

A solution of **50** (4.00 g, 12.3 mmol) in a mixture of THF (30 mL), methanol (30 mL), and water (30 mL) was charged with solid $\text{LiOH}\cdot\text{H}_2\text{O}$ (1.55 g, 36.9 mmol) then the reaction mixture was stirred at room temperature for 1 h. The reaction mixture was charged with $\text{TCEP}\cdot\text{HCl}$ (7.06 g, 24.6 mmol) and stirred for 1 h. The solvent was removed, the residue was dissolved in EtOAc (200 mL), and the solution was washed with saturated aqueous NaHCO_3 solution (100 mL). The EtOAc layer was separated and the aqueous layer was extracted with EtOAc ($2 \times 100\text{ mL}$). The combined organic layers were dried over Na_2SO_4 , filtered, and

concentrated to get crude **51** (3.00 g, yellow liquid) directly used for the next step without further purification. ESI MS m/z 284 $[M + H]^+$.

Preparation of *S*-4-(2-((*tert*-butoxycarbonyl)amino)ethoxy)benzyl 2-methylpropanethioate (54**);**

To a solution of compound **51** (3.00 g, 10.6 mmol) and Et₃N (1.78 mL, 12.72 mmol) in CH₂Cl₂ (150 mL) was added isobutyryl chloride (1.34 g, 12.7 mmol) 0 °C dropwise and stirred at rt for 1h. Water (100 mL) was added to the reaction mixture and extracted with CH₂Cl₂ (3 × 100 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄, and concentrated to afford **54** (2.60 g, 60% over two steps) as colorless liquid. ¹H NMR (400 MHz, CDCl₃) δ 7.20 (d, J = 8.8 Hz, 1H), 6.80 (d, J = 8.8 Hz, 2H), 4.96 (br s, 1H), 4.05 (s, 2H), 3.99 (t, J = 5.2 Hz, 2H), 3.53–3.47 (m, 2H), 2.77–2.69 (m, 1H), 1.44 (s, 9H), 1.20 (s, 3H), 1.18 (s, 3H); ESI MS m/z 354 $[M + H]^+$.

Preparation of *S*-4-(2-aminoethoxy)benzyl 2-methylpropanethioate hydrochloride (55**);**

Compound **54** (2.60 g, 7.36 mmol) was dissolved in 4 N HCl in dioxane (26 mL) at room temperature and the solution was stirred for 2 h. After concentration, the residue was triturated with EtOAc then isolated by filtration to afford the hydrochloric acid salt **55** (1.50 g, 81%) as an off-white solid; ESI MS m/z 254 $[M + H]^+$.

Preparation of *S*-4-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl) amino)ethoxy)benzyl 2-methylpropanethioate hydrochloride (56**);**

A solution of amine **55** (1.70 g, 6.71 mmol) in methanol (75 mL) was charged with D-glucose (2.41 g, 13.4 mmol) and acetic acid (0.82 mL, 13.4 mmol) followed by sodium cyanoborohydride (846 mg, 13.4 mmol) and the resulting mixture was stirred at room temperature for 2 h at 55 °C. Additional D-glucose (0.85 g, 3.36 mmol), AcOH (0.41 mL, 3.36 mmol), and sodium cyanoborohydride (423 mg, 3.36 mmol) were charged and the mixture was stirred for 2 h at 55 °C. Further additional D-glucose (0.85 g, 3.36 mmol), AcOH (0.41 mL, 3.36 mmol), and sodium cyanoborohydride (423 mg, 3.36 mmol) were charged and the mixture was stirred for 2 h at 55 °C. After the solvent was removed under reduced pressure, the residue was purified by reverse-phase chromatography using a C18 Gold column to get pure **56** (1.65 g, 42%) as a white solid. ¹H NMR (400 MHz, CD₃OD) δ 7.23 (d, J = 8.6 Hz, 2H), 6.95 (d, J = 8.6 Hz, 2H), 4.42–4.35 (m, 2H), 4.27–4.17 (m, 2H), 4.05 (s, 2H), 3.93–3.49 (m, 16H), 2.77–2.70 (m, 1H), 1.16 (s, 3H), 1.15 (s, 3H); ¹H NMR (400 MHz, DMSO-*d*₆) δ 8.64 (br s, 1H), 7.22 (d, J = 8.6 Hz, 2H), 6.94 (d, J = 8.6 Hz, 2H), 4.37–4.29 (m, 3H), 4.26–3.82 (m, 12H), 3.76–3.56 (m, 7H), 3.54–3.27 (m, 10H), 2.78–2.72 (m, 1H), 1.12 (s, 3H), 1.10 (s, 3H); ESI MS m/z 582 $[M + H]^+$.

Preparation *S-4-(2-(bis((2R,3R,4R,5R)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy)benzyl 2-methylpropanethioate (57);*

A solution of amine **55** (1.50 g, 5.92 mmol) in methanol (75 mL) was charged with D-mannose (2.13 g, 11.8 mmol) and acetic acid (0.72 mL, 11.8 mmol) followed by sodium cyanoborohydride (735 mg, 11.8 mmol) and the resulting mixture was stirred at room temperature for 2 h at 55 °C. Additional D-mannose (1.07 g, 5.93 mmol), AcOH (0.36 mL, 5.93 mmol), and sodium cyanoborohydride (368 mg, 5.93 mmol) were charged and the mixture was stirred for 2 h at 55 °C. Further additional D-mannose (1.07 g, 5.93 mmol), AcOH (0.36 mL, 5.93 mmol), and sodium cyanoborohydride (368 mg, 5.93 mmol) were charged and the mixture was stirred for 2 h at 55 °C. After the solvent was removed the reaction mixture was crystallized from water: methanol (100:20 mL), to afford the boron complex of the free base **57** (2.25 g, 66%) as a white solid. ESI MS m/z 582 [M + H].⁺

Preparation of *S-4-(2-(bis((2R,3R,4R,5R)-2,3,4,5,6-pentahydroxyhexyl) amino)ethoxy) benzyl 2-methylpropanethioate hydrochloride (59);*

Compound **57** (500 mg, 0.89 mmol) was dissolved in 4 N aq.HCl (0.85 mL) at room temperature and the solution was diluted with water and lyophilized to afford the hydrochloric acid salt **59** (490 g, 92%) as an hygroscopic off-white solid: ¹H NMR (400 MHz, CD₃OD) δ 7.23 (d, J = 8.6 Hz, 2H), 6.96 (d, J = 8.6 Hz, 2H), 4.42–4.36 (m, 2H), 4.18–4.01 (m, 4H), 3.93–3.58 (m, 14H), 3.53–3.44 (m, 2H), 2.77–2.70 (m, 1H), 1.16 (s, 3H), 1.15 (s, 3H). ¹H NMR (400 MHz, DMSO- d_6) δ 8.62 (br s, 1H), 7.23 (d, J = 8.6 Hz, 2H), 6.95 (d, J = 8.6 Hz, 2H), 4.37 (br s, 4H), 4.24–3.77 (m, 16H), 3.76–3.15 (m, 18H), 2.78–2.72 (m, 1H), 1.12 (s, 3H), 1.10 (s, 3H); ESI MS m/z 582 [M + H].⁺

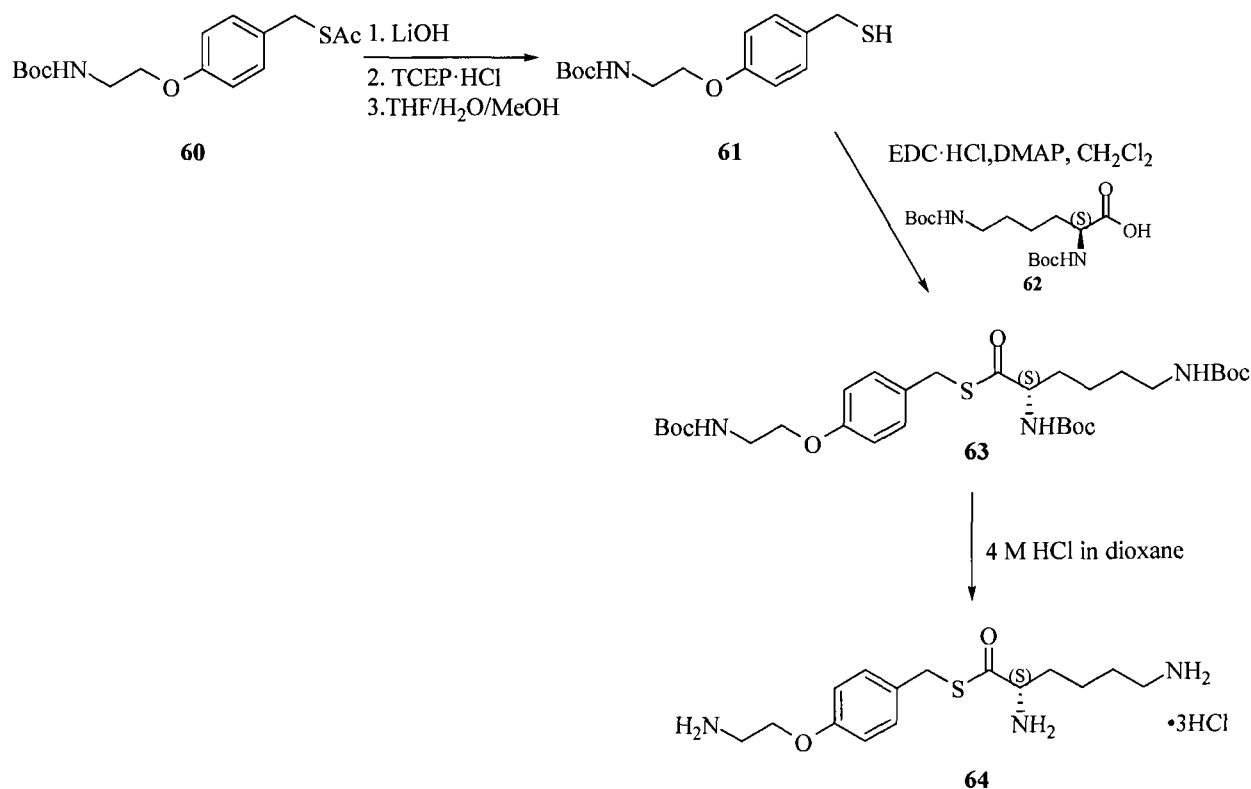
Preparation *(2R,2'R,3R,3'R,4R,4'R,5R,5'R)-6,6'-((2-(4-(mercaptomethyl) phenoxy) ethyl) azanediyl) bis (hexane-1,2,3,4,5-pentaol) hydrochloride (58);*

A solution of compound **57** (1.80 g, 3.09 mmol) in water (50 mL) was charged with solid LiOH·H₂O (520 mg, 12.39 mmol), and the reaction mixture was stirred for 1 h at room temperature, after that solid TCEP·HCl (88 mg, 0.309 mmol) was added and the reaction mixture was stirred at room temperature for 2 h. After completion of the reaction it was acidified with 4 N HCl and the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **58** (1.45 g, 91%) as a colorless gummy solid: ¹H NMR (300 MHz, CD₃OD) δ 7.27 (d, J = 8.6 Hz, 2H), 6.98 (d, J = 8.6 Hz, 2H), 4.43–4.36 (m, 2H), 4.21–4.07 (m, 2H), 3.94–3.62 (m, 16H), 3.57–3.42 (m, 2H); ESI MS m/z 512 [M + H].⁺

General Procedure: All reagent and solvents were purchased from Aldrich Chemical Corp. Chem-Impex International Inc. and TCI chemical industry Co. Ltd. NMR spectra were obtained on either a Bruker AC 400 (^1H NMR at 400 MHz) or a Bruker AC 300 (^1H NMR at 300 MHz). Solvents CDCl_3 , CD_3OD and $\text{DMSO}-d_6$ were purchased from Aldrich or Cambridge Isotope Laboratories, unless otherwise specified. Chemical shifts are reported in ppm relative to tetramethylsilane (TMS) as the internal standard. Data is reported as follows: chemical shift, integration, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, br = broad, m = multiplet), and coupling constants (Hz). Flash chromatography was performed on a Combiflash system (Combiflash Rf, Teledyne Isco) charged with silica gel column (Redi Sep. Rf, Teledyne Isco) or reverse phase column (High performance C18 Gold column). ESI Mass spectra were obtained on a Shimadzu LCMS-2010 EV Mass Spectrometer. HPLC analyses were obtained using a Waters XTerra MS C18 $5\mu\text{m}$ $4.6 \times 150\text{mm}$ Analytical Column detected at 220 nm (unless otherwise specified) on a Shimadzu Prominence HPLC system. All reactions are monitored by TLC and LCMS and for polar compound reactions are monitored by HPLC and LCMS analysis.

15. Preparation of Hydrochloride salt of (S)-S-4-(2-aminoethoxy) benzyl 2,6-diaminohexanethioate (64);

Scheme 15



Preparation of *tert*-butyl (2-(4-(mercaptomethyl)phenoxy)ethyl)carbamate (61);

A solution of **60** (500 mg, 1.53 mmol) in a mixture of THF (50 mL), methanol (10 mL), and water (20 mL) was charged with solid LiOH•H₂O (258 mg, 6.15 mmol), followed by the addition of TCEP•HCl (880 mg, 3.06 mmol) and the reaction mixture was stirred at room temperature for 2 h. After completion of the reaction it was acidified with 4 N HCl and the residue was partitioned between saturated water (10 mL) and EtOAc (100 mL). The organic layer was separated and the aqueous layer was extracted with EtOAc (2 × 50 mL). The combined organic layers were dried over Na₂SO₄, filtered, and concentrated to afford compound **61** (380 mg, 88%) as a off-white gummy solid: ¹H NMR (400 MHz, CDCl₃) δ 7.23 (d, *J* = 8.4 Hz, 2H), 6.83 (d, *J* = 8.4 Hz, 2H), 4.97 (br s, 1H), 4.00 (t, *J* = 5.2 Hz, 2H), 3.70 (d, *J* = 7.4 Hz, 2H), 3.54–3.50 (m, 2H), 1.72 (t, *J* = 7.4 Hz, 1H), 1.45(s, 9H); ESI MS *m/z* 284 [M + H].⁺

Preparation of (S)-S-4-(2-((*tert*-butoxycarbonyl)amino)ethoxy)benzyl 2,6-bis((*tert*-butoxycarbonyl)amino)hexanethioate (63);

Compound **61** (320 mg, 1.14 mmol) and acid **62** (432 mg, 1.25 mmol) were dissolved in CH₂Cl₂ (100 mL), added EDC•HCl (326 mg, 1.71 mmol) and DMAP (7.0 mg, 0.057 mmol) portion wise at room temperature. The reaction mixture was stirred at room temperature for 16 h, after completion of the reaction; the solution was quickly washed with saturated aqueous NaHCO₃ (2 × 50 mL) followed by brine (50 mL). The organic layer was dried over Na₂SO₄ and concentrated. The residue was purified by column chromatography to afford compound **63** (620 mg, 89%) as an off-white solid: ¹H NMR (400 MHz, CDCl₃) δ 7.18 (d, *J* = 8.8 Hz, 2H), 6.80 (d, *J* = 8.8 Hz, 2H), 5.11–4.98 (m, 2H), 4.54 (br s, 1H), 4.33 (br s, 1H), 4.05 (br s, 2H), 3.99 (t, *J* = 5.2 Hz, 2H), 3.53–3.45 (m, 2H), 3.12–3.08 (m, 2H), 1.88–1.78 (m, 1H), 1.53–1.32 (m, 34H); ESI MS *m/z* 612 [M + H].⁺

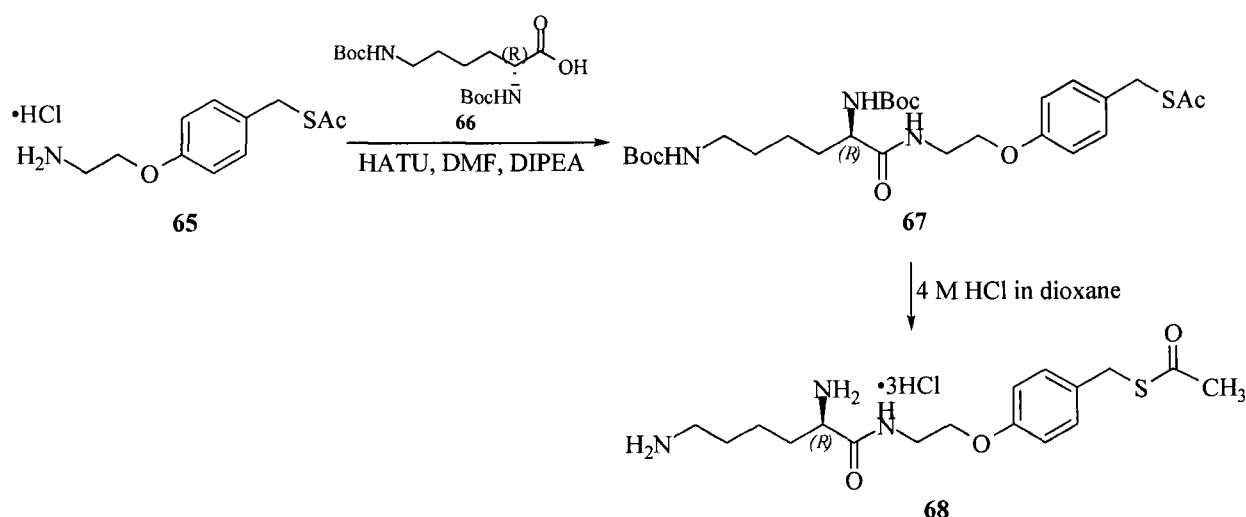
Preparation of Hydrochloride salt of (S)-S-4-(2-aminoethoxy) benzyl 2,6-diaminohexanethioate (64);

Compound **63** (550 mg, 0.90 mmol) was dissolved in 4 N HCl in dioxane (10 mL) at room temperature, and the solution was stirred at same temperature for 2 h. After removal of the solvent, the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **564** (190 mg, 50%) as an hygroscopic off-white solid: ¹H NMR (400 MHz, CD₃OD) δ 7.31 (d, *J* = 8.8 Hz, 2H), 6.96 (d, *J* = 8.8 Hz, 2H), 4.29–4.18 (m, 5H), 3.35 (t, *J* = 4.8 Hz, 2H), 2.92 (t, *J* = 8.0 Hz, 2H), 2.06–1.90 (m, 2H), 1.73–1.48 (m, 4H); ¹H NMR

(400 MHz, DMSO- d_6) δ 8.70 (br s, 3H), 8.28 (br s, 3H), 8.06 (br s, 3H), 7.29 (d, J = 8.8 Hz, 2H), 6.95 (d, J = 8.8 Hz, 2H), 4.22–4.15 (m, 5H), 3.21–3.14 (m, 2H), 2.74–2.66 (m, 2H), 1.86–1.77 (m, 2H), 1.61–1.49 (m, 2H), 1.44–1.27 (m, 2H). ESI MS m/z 312 $[M + H]^+$.

16. Preparation of Hydrochloride salt of (*R*)-*S*-4-(2-(2,6-diaminohexanamido)ethoxy)benzyl ethanethioate (68);

Scheme 16



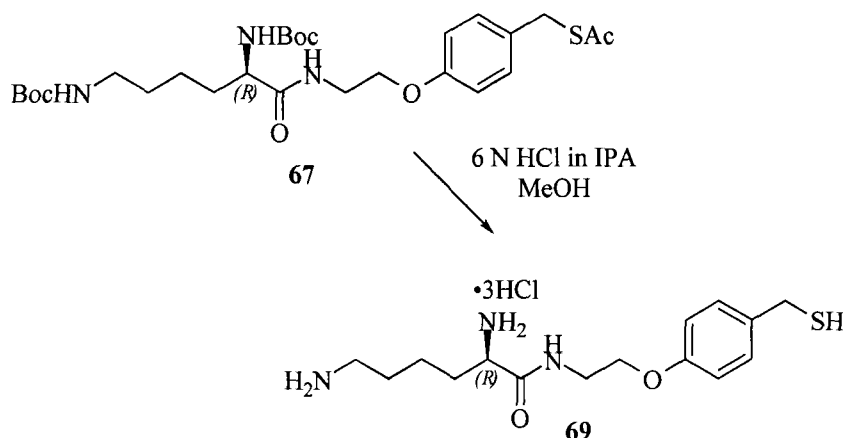
Preparation of (*R*)-*S*-4-(2-(2,6-bis((tert-butoxycarbonyl)amino)hexanamido) ethoxy)benzyl ethanethioate (67);

Compound **65** (1.00 g, 4.44 mmol) and acid **66** (1.69 mg, 4.88 mmol) were dissolved in DMF (50 mL) and treated with DIPEA (1.14 g, 8.88 mmol) and HATU (2.53 g, 6.66 mmol). The reaction mixture was stirred at room temperature for 12 h. The solvent was removed under reduced pressure, the residue was dissolved in EtOAc (100 mL), and the solution was quickly washed with saturated aqueous NaHCO_3 (2×100 mL) followed by brine (100 mL). The organic layer was dried over Na_2SO_4 and concentrated. The residue was purified by column chromatography to afford compound **67** (1.60 g, 67%) as an off-white solid: ^1H NMR (300 MHz, CDCl_3) δ 7.19 (d, J = 8.4 Hz, 2H), 6.81 (d, J = 8.4 Hz, 2H), 6.52 (br s, 1H), 5.07 (br s, 2H), 4.53 (br s, 1H), 4.08–3.95 (m, 5H), 3.68–3.60 (m, 2H), 3.11–3.01 (m, 2H), 2.33 (s, 3H), 2.04 (br s, 1H), 1.89–1.56 (m, 4H), 1.53–1.19 (m, 24H); ESI MS m/z 554 $[M + H]^+$.

Preparation of Hydrochloride salt of (R)-S-4-(2-(2,6-diaminohexanamido)ethoxy)benzyl ethanethioate (68);

Compound **67** (300 mg, 0.542 mmol) was dissolved in 4 N HCl in dioxane (10 mL) at room temperature, and the solution was stirred at same temperature for 2 h. After removal of the solvent, the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **68** (150 mg, 60%) as an hygroscopic off-white solid: ^1H NMR (400 MHz, CD_3OD) δ 7.20 (d, J = 8.6 Hz, 2H), 6.85 (d, J = 8.6 Hz, 2H), 4.08–4.05 (m, 4H), 3.85 (t, J = 6.6 Hz, 1H), 3.71–3.66 (m, 1H), 3.59–3.54 (m, 1H), 2.85–2.81 (m, 2H), 2.33 (s, 3H), 1.89–1.81 (m, 2H), 1.68–1.62 (m, 2H), 1.49–1.43 (m, 2H); ^1H NMR (400 MHz, $\text{DMSO}-d_6$) δ 8.75 (t, J = 5.4 Hz, 1H), 7.91 (br s, 5H), 7.21 (d, J = 8.8 Hz, 2H), 6.87 (d, J = 8.8 Hz, 2H), 4.05–3.99 (m, 4H), 3.69 (t, J = 6.8 Hz, 1H), 3.52–3.42 (m, 2H), 2.69 (t, J = 7.4 Hz, 2H), 2.33 (s, 3H), 1.72–1.66 (m, 2H), 1.56–1.51 (m, 2H); ESI MS m/z 354 $[\text{M} + \text{H}]^+$.

17. Preparation of Hydrochloride salt of (R)-2,6-diamino-N-(2-(4-(mercaptomethyl)phenoxy)ethyl)hexanamide (69);
Scheme 17

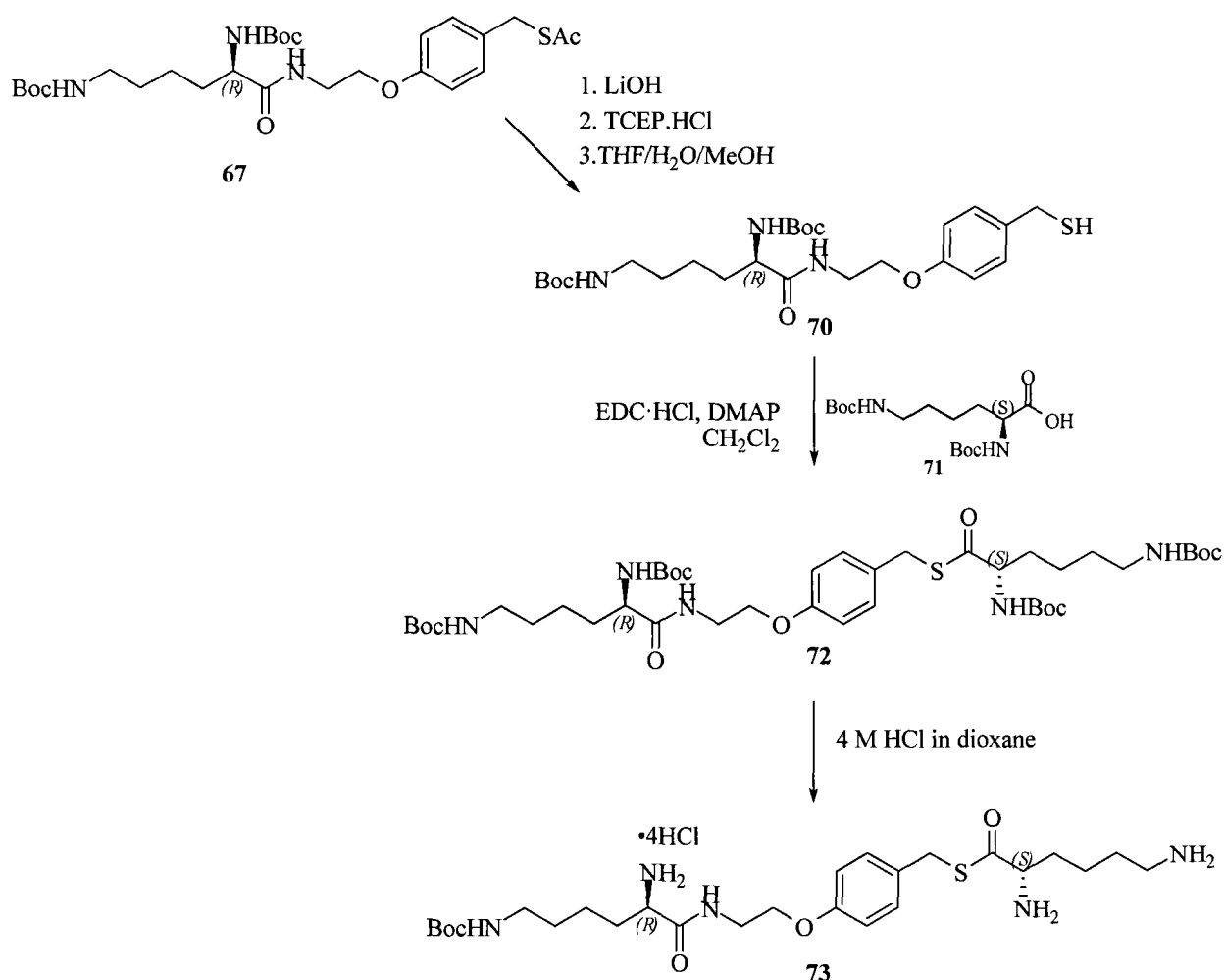


Preparation of Hydrochloride salt of (R)-2,6-diamino-N-(2-(4-(mercaptomethyl)phenoxy)ethyl)hexanamide (69);

Compound **67** (350 mg, 0.632 mmol) was dissolved in methanol (10 mL) followed by the addition of 6 N HCl in isopropanol (20 mL) drop wise at room temperature, and the solution was stirred at same temperature for 12 h. After removal of the solvent, the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **69** (207 mg, 92%) as a hygroscopic off-white solid: ^1H NMR (300 MHz, CD_3OD) δ 7.24 (d, J = 8.6 Hz, 2H), 6.87 (d, J = 8.6 Hz, 2H), 4.09–4.03 (m, 2H), 3.88 (t, J = 6.4 Hz, 1H), 3.71–3.55 (m, 4H), 2.81 (t, J = 8.0 Hz, 2H), 1.92–1.82 (m, 2H), 1.68–1.62 (m, 2H), 1.50–1.39 (m, 2H); ^1H NMR (300 MHz, $\text{DMSO}-d_6$) δ 8.85 (t, J = 5.2 Hz, 1H), 8.30–8.04 (m, 6H), 7.26 (d, J = 8.6

Hz, 2H), 6.88 (d, $J = 8.6$ Hz, 2H), 4.02 (br s, 2H), 3.77–3.67 (m, 3H), 3.52–3.41 (m, 3H), 2.80–2.68 (m, 3H), 1.76–1.69 (m, 2H), 1.60–1.51 (m, 2H), 1.39–1.29 (m, 2H); ESI MS m/z 312 $[M + H]^+$

18. Preparation of Hydrochloride salt of (S)-S-4-(2-((R)-2-amino-6-((tert-butoxycarbonyl)amino)hexanamido)ethoxy)benzyl 2,6-diaminohexanethioate (73); Scheme 18



Preparation of (R)-di-tert-butyl (6-((2-(4-(mercaptomethyl)phenoxy)ethyl)amino)-6-oxohexane-1,5-diyl)dicarbamate (70);

A solution of **67** (700 mg, 1.26 mmol) in a mixture of THF (50 mL), methanol (10 mL), and water (20 mL) was charged with solid LiOH·H₂O (212 mg, 5.06 mmol), followed by the addition of TCEP·HCl (720 mg, 2.52 mmol) and the reaction mixture was stirred at room

temperature for 2 h. After completion of the reaction it was acidified with 1 N HCl and the residue was partitioned between saturated water (10 mL) and EtOAc (100 mL). The organic layer was separated and the aqueous layer was extracted with EtOAc (2 × 50 mL). The combined organic layers were dried over Na₂SO₄, filtered, and concentrated to afford compound **70** (500 mg, 78%) as an off-white solid: ¹H NMR (300 MHz, CDCl₃) δ 7.23 (d, *J* = 8.6, 2H), 6.83 (d, *J* = 8.6, 2H), 6.58 (br s, 1H), 5.10 (br s, 1H), 4.55 (br s, 1H), 4.08–3.97 (m, 3H), 3.72–3.58 (m, 4H), 3.11–2.98 (m, 2H), 1.90–1.53 (m, 6H), 1.51–1.17 (m, 25H); ESI MS *m/z* 512 [M + H].⁺

Preparation of (S)-S-4-(2-((R)-2,6-bis((tert-butoxycarbonyl)amino)hexanamido)ethoxy)benzyl 2,6-bis((tert-butoxycarbonyl)amino)hexanethioate (72);

Compound **70** (500 mg, 0.97 mmol) and acid **71** (372 mg, 1.07 mmol) were dissolved in CH₂Cl₂ (100 mL), added EDC.HCl (277 mg, 1.45 mmol) and DMAP (6.0 mg, 0.048 mmol) portion wise at room temperature. The reaction mixture was stirred at room temperature for 12 h, after completion of the reaction; the solution was quickly washed with saturated aqueous NaHCO₃ (2 × 50 mL) followed by brine (50 mL). The organic layer was dried over Na₂SO₄ and concentrated. The residue was purified by column chromatography to afford compound **72** (650 mg, 80%) as an off-white solid: ¹H NMR (400 MHz, CDCl₃) δ 7.18 (d, *J* = 8.6, 2H), 6.79 (d, *J* = 8.6, 2H), 6.53 (br s, 1H), 5.10 (br s, 1H), 4.57 (br s, 2H), 4.32 (br s, 1H), 4.08–3.98 (m, 5H), 3.68–3.60 (m, 2H), 3.14–3.01 (m, 4H), 1.90–1.73 (m, 2H), 1.67–1.60 (m, 3H), 1.52–1.30 (m, 45H); ESI MS *m/z* 840 [M + H].⁺

Preparation of Hydrochloride salt of (S)-S-4-(2-((R)-2-amino-6-((tert-butoxycarbonyl)amino)hexanamido)ethoxy)benzyl 2,6-diaminohexanethioate (73);

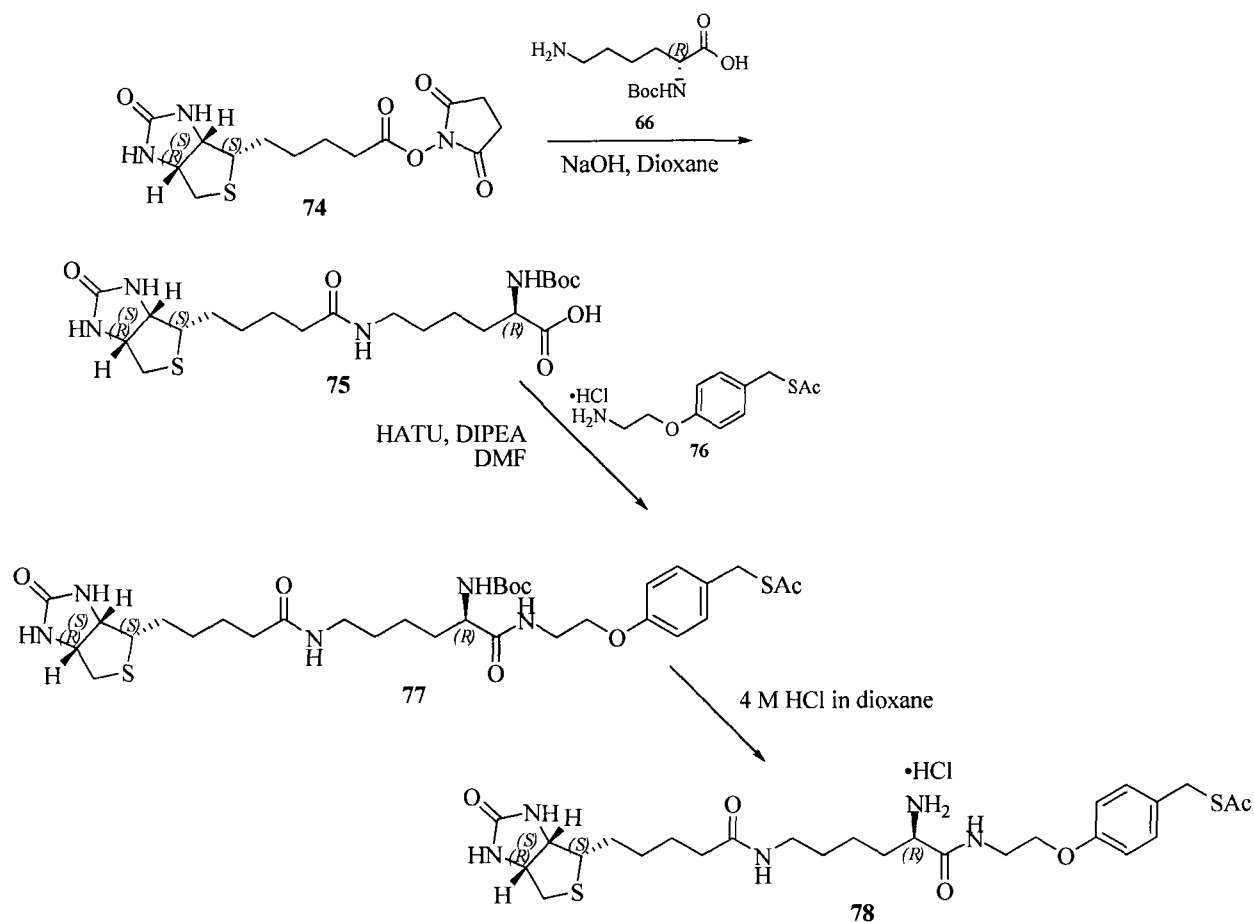
Compound **72** (650 mg, 0.773 mmol) was dissolved in 4 N HCl in dioxane (10 mL) at room temperature, and the solution was stirred at same temperature for 2 h. After removal of the solvent, the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **73** (300 g, 66%) as a hygroscopic off-white solid: ¹H NMR (300 MHz, CD₃OD) δ 7.27 (d, *J* = 8.4, 2H), 6.89 (d, *J* = 8.4, 2H), 4.25 (br s, 3H), 4.07 (t, *J* = 5.4, 2H), 3.91 (t, *J* = 6.6, 1H), 3.70–3.59 (m, 3H), 2.96–2.80 (m, 4H), 2.06–1.80 (m, 4H), 1.78–1.61 (m, 4H), 1.57–1.40 (m, 4H);

¹H NMR (300 MHz, DMSO-*d*₆) δ 8.90 (t, *J* = 5.4, 1H), 8.73 (br s, 3H), 8.33 (br s, 3H), 8.08 (br s, 6H), 7.27 (d, *J* = 8.6, 2H), 6.90 (d, *J* = 8.6, 2H), 4.21 (br s, 3H), 4.07–3.96 (m, 2H),

3.77 (br s, 1H), 3.56–3.41 (m, 2H), 2.70 (br s, 4H), 1.84–1.69 (m, 4H), 1.64–1.48 (m, 4H), 1.47–1.34 (m, 4H); ESI MS m/z 540 $[M + H]^+$.

19. Preparation of Hydrochloride salt of *S*-4-(2-((*R*)-2-amino-6-(5-((3*aS*,4*S*,6*aR*)-2-oxohexahydro-1*H*-thieno[3,4-*d*]imidazol-4-yl)pentanamido) hexanamido)ethoxy) benzyl ethanethioate (78);

Scheme 19



Preparation of (*R*)-2-((*tert*-butoxycarbonyl)amino)-6-(5-((3*aS*,4*S*,6*aR*)-2-oxohexahydro-1*H*-thieno[3,4-*d*]imidazol-4-yl)pentanamido)hexanoic acid (75);

Compound 74 (900 mg, 2.63 mmol) and acid 66 (973 mg, 3.95 mmol) were dissolved in dioxane (50 mL), added 6 N NaOH (10 mL) drop wise at room temperature. The reaction mixture was stirred at room temperature for 12 h, after completion of the reaction it was diluted with EtOAc (100 mL) and the mixture was washed with saturated aqueous NaHCO₃ (2 × 100 mL) followed by brine (100 mL). The organic layer was dried over Na₂SO₄ and concentrated. The residue was purified by column chromatography to afford compound 75

(700 mg, 56%) as an off-white solid: ^1H NMR (300 MHz, CD_3OD) δ 4.53–4.49 (m, 1H), 4.34–4.30 (m, 1H), 4.06 (br s, 1H), 3.25–3.15 (m, 3H), 2.97–2.91 (m, 1H), 2.71–2.68 (m, 1H), 2.23–2.17 (m, 2H), 1.80–1.50 (m, 8H), 1.45 (s, 13 H); ESI MS m/z 473 $[\text{M} + \text{H}]^+$.

Preparation of *S*-4-(2-((*R*)-2-((*tert*-butoxycarbonyl)amino)-6-(5-((3*aS*,4*S*,6*aR*)-2-oxohexahydro-1*H*-thieno[3,4-*d*]imidazol-4-yl)pentanamido)hexanamido)ethoxy)benzyl ethanethioate (77);

Compound **75** (700 mg, 1.48 mmol) and amine **76** (367 mg, 1.63 mmol) were dissolved in DMF (50 mL) and treated with DIPEA (381 mg, 2.96 mmol) and HATU (843 mg, 2.22 mmol). The reaction mixture was stirred at room temperature for 12 h. The solvent was removed under reduced pressure, the residue was dissolved in EtOAc (100 mL), and the solution was quickly washed with saturated aqueous NaHCO_3 (2×100 mL) followed by brine (100 mL). The organic layer was dried over Na_2SO_4 and concentrated. The residue was purified by column chromatography to afford compound **77** (725 mg, 71%) as an off-white solid: ^1H NMR (300 MHz, CD_3OD) δ 7.18 (d, $J = 8.4$ Hz, 2H), 6.81 (d, $J = 8.4$ Hz, 2H), 7.11 (br s, 1H), 6.09 (br s, 2H), 5.36 (br s, 1H), 5.24 (br s, 1H), 4.46 (t, $J = 4.4$ Hz, 1H), 4.30 (t, $J = 4.4$ Hz, 1H), 4.06 (br s, 2H), 4.01 (t, $J = 5.2$ Hz, 2H), 3.62 (t, $J = 4.6$ Hz, 2H), 3.23–3.11 (m, 3H), 2.95–2.66 (m, 2H), 2.32 (s, 3H), 2.19 (t, $J = 6.8$ Hz, 2H), 1.82–1.57 (m, 8H), 1.55–1.31 (m, 15H); ESI MS m/z 540 $[\text{M} + \text{H}]^+$.

Preparation of Hydrochloride salt of *S*-4-(2-((*R*)-2-amino-6-(5-((3*aS*,4*S*,6*aR*)-2-oxohexahydro-1*H*-thieno[3,4-*d*]imidazol-4-yl)pentanamido)hexanamido)ethoxy)benzyl ethanethioate (78);

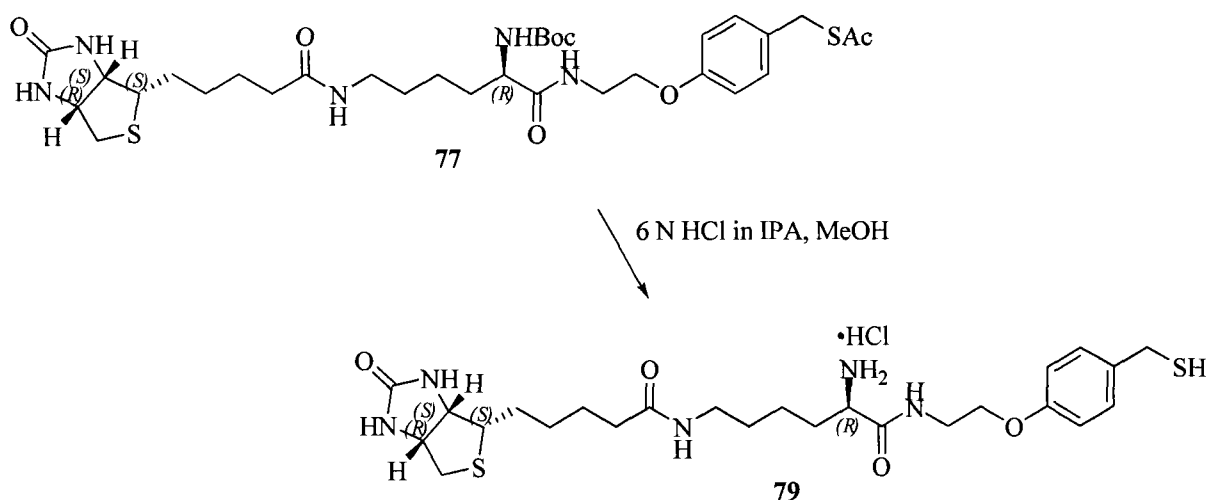
Compound **77** (250 mg, 0.368 mmol) was dissolved in 4 N HCl in dioxane (5 mL) at room temperature, and the solution was stirred at same temperature for 2 h. After removal of the solvent, the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **78** (150 mg, 70%) as a hygroscopic off-white gum: ^1H NMR (300 MHz, CD_3OD) δ 7.21 (d, $J = 8.6$ Hz, 2H), 6.87 (d, $J = 8.6$ Hz, 2H), 4.57–4.50 (m, 1H), 4.38–4.31 (m, 1H), 4.06 (br s, 4H), 3.87–3.79 (m, 1H), 3.77–3.50 (m, 4H), 3.27–3.16 (m, 1H), 3.14–3.05 (m, 2H), 2.99–2.67 (m, 2H), 2.31 (s, 3H), 2.24–2.15 (m, 2H), 1.90–1.77 (m, 2H), 1.76–1.56 (m, 4H), 1.55–1.31 (m, 6H);

^1H NMR (300 MHz, $\text{DMSO}-d_6$) δ 8.68 (br s, 1H), 8.11 (br s, 3H), 7.72 (br s, 1H), 7.21 (d, $J = 8.6$ Hz, 2H), 6.87 (d, $J = 8.6$ Hz, 2H), 6.38 (br s, 1H), 4.32–4.26 (m, 1H), 4.14–4.08 (m, 1H), 4.07–3.96 (m, 4H), 3.75–3.68 (m, 2H), 3.56–3.46 (m, 3H), 3.13–3.05 (m, 1H), 2.99–2.90 (m,

2H), 2.84–2.78 (m, 1H), 2.59–2.54 (m, 1H), 2.33 (s, 3H), 2.03 (d, $J = 7.2$ Hz, 2H), 1.70–1.19 (m, 12H); ESI MS m/z 616 $[M + H]^+$.

20. Preparation of (*R*)-2-amino-*N*-(2-(4-(mercaptomethyl)phenoxy)ethyl)-6-(5-((3*aS*,4*S*,6*aR*)-2-oxohexahydro-1*H*-thieno[3,4-*d*]imidazol-4-yl)pentanamido)hexanamide hydrochloride (79**);**

Scheme 20



Preparation of (*R*)-2-amino-*N*-(2-(4-(mercaptomethyl)phenoxy)ethyl)-6-(5-((3*aS*,4*S*,6*aR*)-2-oxohexahydro-1*H*-thieno[3,4-*d*]imidazol-4-yl)pentanamido)hexanamide hydrochloride (79**);**

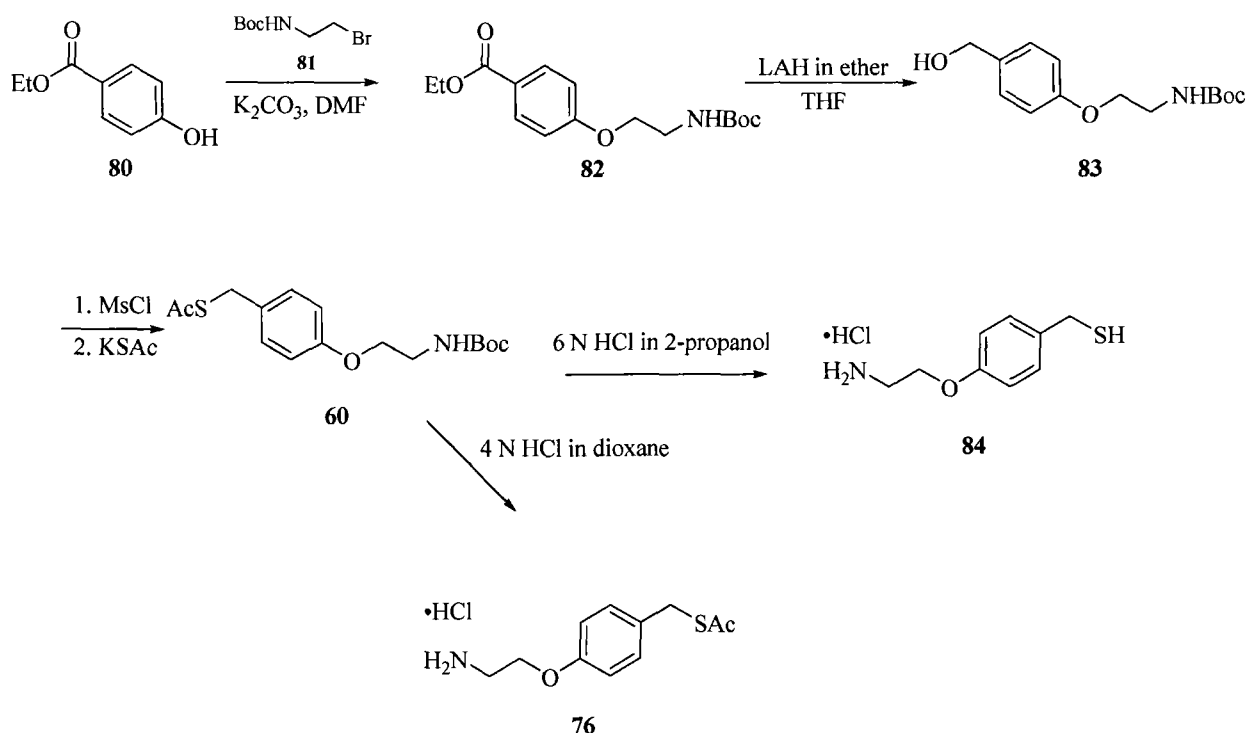
Compound **77** (475 mg, 0.699 mmol) was dissolved in methanol (5 mL) followed by the addition of 6 N HCl in isopropanol (15 mL) drop wise at room temperature, and the solution was stirred at same temperature for 12 h. After removal of the solvent, the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **79** (260 mg, 69%) as a hygroscopic off-white solid: ^1H NMR (400 MHz, CD_3OD) δ 7.24 (d, $J = 8.6$ Hz, 2H), 6.87 (d, $J = 8.6$ Hz, 2H), 4.49–4.46 (m, 1H), 4.30–4.27 (m, 1H), 4.08–4.05 (m, 2H), 3.80 (t, $J = 6.4$ Hz, 1H), 3.73–3.68 (m, 3H), 3.59–3.53 (m, 1H), 3.21–3.17 (m, 1H), 3.09 (t, $J = 7.2$ Hz, 2H), 2.94–2.89 (m, 1H), 2.69 (d, $J = 12.4$ Hz, 1H), 2.17 (t, $J = 7.4$ Hz, 2H), 1.84–1.35 (m, 12H);

^1H NMR (300 MHz, $\text{DMSO}-d_6$) δ 8.68 (t, $J = 5.4$ Hz, 1H), 8.09 (br s, 3H), 7.73 (t, $J = 5.4$ Hz, 1H), 7.25 (d, $J = 8.4$ Hz, 2H), 6.88 (d, $J = 8.4$ Hz, 2H), 6.36 (d, $J = 11.2$ Hz, 2H), 4.30 (t, $J = 7.2$ Hz, 1H), 4.13–3.97 (m, 3H), 3.75–3.62 (m, 3H), 3.57–3.42 (m, 2H), 3.17–3.05 (m, 1H),

2.97–2.91 (m, 2H), 2.84–2.70 (m, 2H), 2.57 (d, $J = 12.4$ Hz, 1H), 2.04 (t, $J = 7.2$ Hz, 2H), 1.69–1.42 (m, 6H), 1.41–1.19 (m, 6H); ESI MS m/z 574 $[M + H]^+$.

21. Preparation of (4-(2-aminoethoxy)phenyl)methanethiol hydrochloride (84) and Preparation of *S*-4-(2-aminoethoxy)benzyl ethanethioate hydrochloride (76);

Scheme 21



Preparation of ethyl 4-(2-((tert-butoxycarbonyl)amino)ethoxy)benzoate (82);

A solution of compound **80** (8.00 g, 48.2 mmol) in DMF (100 mL) was charged with K_2CO_3 (26.6 g, 192.8 mmol) and stirred at room temperature for 5 min. The above reaction mixture was charged with compound **21** (21.5 g, 96.3 mmol) and the reaction mixture was stirred at room temperature for 20 h. The reaction mixture was diluted with water (300 mL) and extracted with EtOAc (3×300 mL). The combined organic layer was concentrated and the residue was purified by column chromatography to afford compound **82** (10.2 g, 69%) as a white gum: 1H NMR (400 MHz, $CDCl_3$) δ 7.98 (d, $J = 8.8$ Hz, 2H), 6.90 (d, $J = 8.8$ Hz, 2H), 5.03 (br s, 1H), 4.37–4.31 (m, 2H), 4.07 (t, $J = 5.2$ Hz, 2H), 3.57–3.53 (m, 2H), 1.45 (s, 9H), 1.37 (t, $J = 7.2$ Hz, 2H); ESI MS m/z 310 $[M + H]^+$.

Preparation of *tert*-butyl (2-(4-(hydroxymethyl)phenoxy)ethyl)carbamate (83);

A solution of compound **82** (10.0 g, 32.3 mmol) in THF (500 mL) was charged with lithium aluminum hydride (1 M solution in diethyl ether, 66.4 mL, 32.3 mmol) drop wise at 0 °C. The resulting reaction mixture was stirred at 0 °C for 1 h and quenched with ice-cold water at 0 °C. The reaction mixture was diluted with EtOAc (300 mL) and filtered through a Celite pad, and the Celite pad was washed with EtOAc (2 × 300 mL). The filtrate was concentrated under vacuum and it was purified by column chromatography to afford compound **83** (6.10 g, 71%) as a gummy solid: ¹H NMR (400 MHz, CD₃Cl) δ 7.27 (d, *J* = 8.4 Hz, 2H), 6.86 (d, *J* = 8.4 Hz, 2H), 5.05 (br s, 1H), 4.60 (s, 2H), 3.99 (t, *J* = 5.2 Hz, 2H), 3.54–3.46 (m, 2H), 2.03 (br s, 1H), 1.44 (s, 9H); ESI MS *m/z* 268 [M + H].⁺

Preparation of *S*-4-(2-((*tert*-butoxycarbonyl)amino)ethoxy)benzyl ethanethioate (60); SG-SUR-G-48/51

A solution of **23** (6.10 g, 22.8 mmol) in CH₂Cl₂ (100 mL) was charged with Et₃N (2.76 g, 27.4 mmol) followed by methanesulfonyl chloride (3.12 g, 27.4 mmol) at 0 °C and stirred at room temperature for 2 h. The reaction mixture was diluted with water (100 mL) and extracted with CH₂Cl₂ (3 × 150 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄, and concentrated to afford the mesylated product (8.20 g, crude) as yellow oil, which was directly used for the next step without further purification: ESI MS *m/z* 346 [M + H].⁺

The above crude product (8.20 g, crude) in DMF (100 mL) was charged with KSAc (6.70 g, 59.4 mmol) and stirred at room temperature for 2 h. The solvent was removed and the residue was partitioned between water (100.0 mL) and EtOAc (100 mL). The EtOAc layer was separated and the aqueous layer was extracted with EtOAc (2 × 100 mL). The combined organic layer was concentrated and the residue was purified by column chromatography to afford compound **1** (4.80 g, 65% over two steps) as a yellow solid: ¹H NMR (400 MHz, CD₃OD) δ 6.91 (s, 2H), 4.10 (s, 4H), 3.99 (t, *J* = 5.7 Hz, 4H), 3.41 (t, *J* = 5.6 Hz, 4H), 2.31 (s, 6H), 1.43 (s, 18); ESI MS *m/z* 326 [M + H].⁺

Preparation of (4-(2-aminoethoxy)phenyl)methanethiol hydrochloride (84);

Compound **60** (325 mg, 1.0 mmol) was dissolved in methanol (5 mL) followed by the addition of 6 N HCl in isopropanol (1.0 mL, 6.0 mmol) drop wise at room temperature, and the solution was stirred at same temperature for 48 h. After removal of the solvent, the residue was triturated with EtOAc to afford the hydrochloric acid salt **84** (190 mg, 87%) as a hygroscopic off-white solid: ^1H NMR (400 MHz, CD_3OD) δ 7.28 (d, $J = 8.6$, 3.0 Hz, 2H), 6.93 (d, $J = 8.6$, 3.0 Hz, 2H), 4.20 (t, $J = 5.0$ Hz, 2H), 3.69 (s, 2H), 3.34 (dd, $J = 5.0$, 4.0 Hz, 2H).

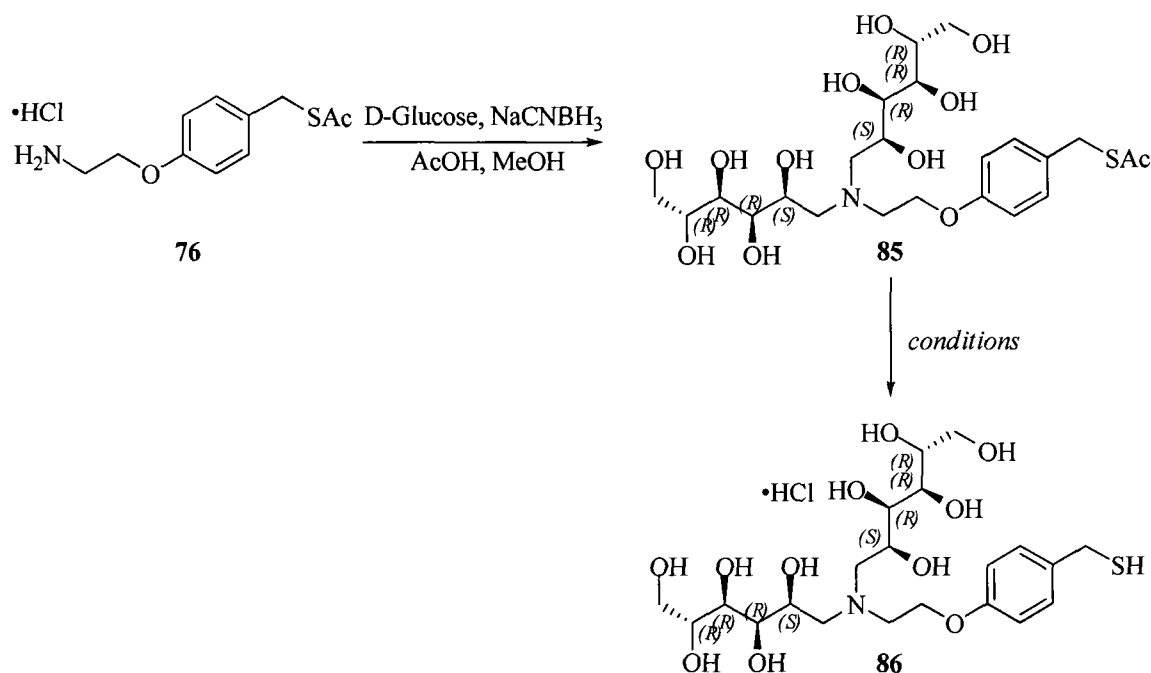
400 MHz (DMSO- d_6): δ 7.90 (brs, 3H) 7.28 (d, $J = 8.8$, 3.0 Hz, 2H), 6.92 (d, $J = 8.8$, 3.0 Hz, 2H), 4.13 (t, $J = 5.2$ Hz, 2H), 3.69 (d, $J = 5.8$ Hz, 2H), 3.19 (t, $J = 5.2$ Hz, 2H), 2.77 (t, $J = 6.8$ Hz, 1H); ESI MS m/z 184 $[\text{M} + \text{H}]^+$.

Preparation of S-4-(2-aminoethoxy)benzyl ethanethioate hydrochloride (76);

Compound **60** (5.00 g, 15.4 mmol) was dissolved in 4 N HCl in dioxane (20 mL) at room temperature and the solution was stirred for 1 h. After concentration, the residue was triturated with MTBE to afford the hydrochloric acid salt **76** (3.6 g, 90%) as an off-white solid: ^1H NMR (400 MHz, CD_3OD) δ 7.23 (d, $J = 8.5$, 3.0 Hz, 2H), 6.92 (d $J = 8.5$, 3.0 Hz, 2H), 4.20 (dd, $J = 5.2$, 4.8 Hz, 2H), 4.07 (s, 2H), 3.34 (dd, $J = 5.1$, 4.0 Hz, 2H), 2.31 (s, 3H); 400 MHz (DMSO- d_6): δ 8.15 (brs, 3H) 7.23 (d, $J = 8.4$, 3.0 Hz, 2H), 6.91 (d, $J = 8.4$, 3.0 Hz, 2H), 4.15 (t, $J = 5.4$ Hz, 2H), 4.06 (s, 2H), 3.18 (t, $J = 5.2$ Hz, 2H), 2.33 (s, 3H); ESI MS m/z 226 $[\text{M} + \text{H}]^+$.

22. Preparation of *S*-4-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy) benzyl ethanethioate (**25**); SG-SUR-G-05; ALB187326 and Preparation of the Hydrochloride salt of (2*R*,2'*R*,3*R*,3'*R*,4*R*,4'*R*,5*S*,5'*S*)-6,6'-((2-(4-(mercaptomethyl)phenoxy)ethyl)azanediyl)bis(hexane-1,2,3,4,5-pentaol) (**86**);

Scheme 22



Preparation of *S*-4-(2-(bis((2*S*,3*R*,4*R*,5*R*)-2,3,4,5,6-pentahydroxyhexyl)amino)ethoxy) benzyl ethanethioate (85**);**

A solution of amine **76** (300 mg, 1.33 mmol) in methanol (50 mL) was charged with D-Glucose (720 mg, 4.0 mmol) and acetic acid (0.3 mL) successively and stirred at room temperature for 10 min. Sodium cyanoborohydride (252 mg, 4.0 mmol) was added to the above reaction mixture and the resulting reaction mixture was stirred at room temperature for 24 h. Additional D-Glucose (2.0 equiv), AcOH (0.3 mL), and Sodium cyanoborohydride (2.0 equiv) were charged and the mixture was stirred for another 24 h. Further additional D-Glucose (3.0 equiv), AcOH (0.3 mL), and Sodium cyanoborohydride (3.0 equiv) were charged and the mixture was stirred for another 48 h. After the solvent was removed under reduced pressure, the residue was neutralized with saturated aqueous NaHCO₃ and purified by reverse-phase chromatography using a C18 Gold column to get pure **85** (450 mg, 61%) as a white solid: ¹H NMR (400 MHz, CD₃OD) δ 7.19 (d, *J* = 8.6 Hz, 2H), 6.89 (d, *J* = 8.6 Hz, 2H), 4.16 (br s, 2H), 4.06 (s, 2H), 3.97 (br s, 2H), 3.80–3.73 (m, 4H), 3.72–3.59 (m, 7H), 3.34 (br s, 1H), 3.25–3.12 (m, 2H), 2.96 (br s, 3H), 2.30 (s, 3H);

^1H NMR (400 MHz, DMSO- d_6) δ 7.23–7.18 (m, 2H), 6.92–6.87 (m, 2H), 4.20–4.14 (m, 10H), 4.11–3.93 (m, 5H), 3.76–3.53 (m, 6H), 3.51–3.33 (m, 8H), 2.95–2.84 (m, 1H), 2.72–2.54 (m, 2H), 2.32 (s, 3H); ESI MS m/z 554 $[\text{M} + \text{H}]^+$

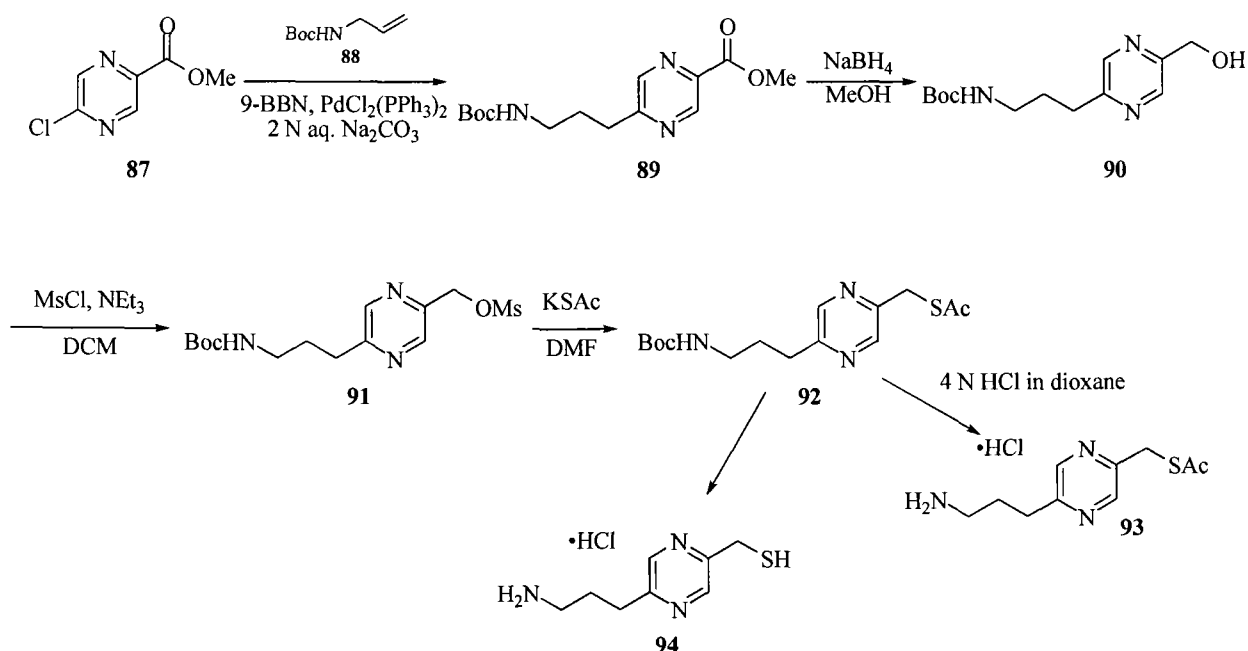
Preparation of the Hydrochloride salt of (2*R*,2'*R*,3*R*,3'*R*,4*R*,4'*R*,5*S*,5'*S*)-6,6'-((2-(4-(mercaptomethyl)phenoxy)ethyl)azanediyl)bis(hexane-1,2,3,4,5-pentaol) (86);

Compound **85** (200 mg, 0.361 mmol) was dissolved in methanol (5 mL) followed by the addition of 6 N HCl in isopropanol (15 mL) drop wise at room temperature, and the solution was stirred at same temperature for 12 h. After removal of the solvent, the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **86** (50 mg, 28%) as an hygroscopic off-white solid: ^1H NMR (300 MHz, CD_3OD) δ 7.27 (d, $J = 8.6$, 2H), 6.96 (d, $J = 8.6$, 2H), 4.39 (br s, 2H), 4.21 (br s, 2H), 3.83 (br s, 3H), 3.80–3.73 (m, 3H), 3.71–3.60 (m, 10H), 3.59–3.47 (m, 4H);

^1H NMR (300 MHz, DMSO- d_6) δ 8.56 (br s, 1H), 7.55 (d, $J = 8.6$, 2H), 6.94 (d, $J = 8.6$, 2H), 5.53–5.40 (m, 2H), 4.80 (br s, 2H), 4.63–4.28 (m, 8H), 4.06 (br s, 2H), 3.74–3.57 (m, 8H), 3.54–3.36 (m, 10H), 2.76 (t, $J = 7.4$, 1H). ESI MS m/z 512 $[\text{M} + \text{H}]^+$

23. Preparation of *S*-((5-(3-aminopropyl)pyrazin-2-yl)methyl) ethanethioate hydrochloride (93); and Preparation of (5-(3-aminopropyl)pyrazin-2-yl)methanethiol hydrochloride (94);

Scheme 23



Preparation methyl 5-(3-((tert-butoxycarbonyl)amino)propyl)pyrazine-2-carboxylate (89);

To a solution of compound **88** (1.20 g, 7.64 mmol) in anhydrous THF (100 mL) was added 9-BBN (0.5 M in THF, 38 mL, 19.1 mmol) under argon. After the reaction mixture was stirred for 2 h at room temperature, compound **27** (1.04 g, 6.11 mmol), Pd(PPh₃)₂Cl₂ (311 mg, 0.38 mmol), and 2 N aq Na₂CO₃ (15 mL) were added at room temperature. The resulting mixture was stirred for additional 1 h. After solvent removed; the residue was partitioned between EtOAc (200 mL) and water (200 mL). The aqueous layer was separated and extracted with EtOAc (2 × 200 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄ and concentrated under vacuum. The crude product was purified by column chromatography to afford compound **89** (900 mg, 53%) as a brown liquid, and directly used for next step; ESI MS *m/z* 296 [M + H].⁺

Preparation of tert-butyl (3-(5-(hydroxymethyl)pyrazin-2-yl)propyl)carbamate (90);

A solution of compound **89** (900 mg, 3.05 mmol) in EtOH (100 mL) was charged with sodium borohydride (400 mg, 15.25 mmol) at 0 °C. The resulting reaction mixture was stirred at rt for 3 h and the residue was partitioned between EtOAc (200 mL) and water (200 mL). The aqueous layer was separated and extracted with EtOAc (2 × 200 mL). The combined organic extracts were washed with brine, dried over Na₂SO₄ and concentrated under vacuum. The crude product was purified by column chromatography to afford

compound **90** (550 mg, 68%) as a brown liquid: ^1H NMR (400 MHz, CD_3Cl) δ 7.27 (d, J = 8.4 Hz, 2H), 6.86 (d, J = 8.4 Hz, 2H), 5.05 (br s, 1H), 4.60 (s, 2H), 3.99 (t, J = 5.2 Hz, 2H), 3.54–3.46 (m, 2H), 2.03 (br s, 1H), 1.44 (s, 9H); ESI MS m/z 268 $[\text{M} + \text{H}]^+$.

Preparation of *S*-(5-(3-((*tert*-butoxycarbonyl)amino)propyl)pyrazin-2-yl)methyl methanesulfonate (91**);**

A solution of **90** (260 mg, 0.97 mmol) in CH_2Cl_2 (30 mL) was charged with Et_3N (117 mg, 1.16 mmol) followed by methanesulfonyl chloride (132 mg, 1.16 mmol) at 0 °C and stirred at room temperature for 2 h. The reaction mixture was diluted with water (100 mL) and extracted with CH_2Cl_2 (2×50 mL). The combined organic extracts were washed with brine, dried over Na_2SO_4 , and concentrated to afford **91** (210 mg, 63%) as yellow oil, which was directly used for the next step without further purification: ^1H NMR (300 MHz, CD_3Cl) δ 8.62 (s, 1H), 8.46 (s, 1H), 5.33 (s, 2H), 4.63 (br s, 1H), 3.23–3.16 (m, 2H), 3.11 (s, 3H), 2.88 (t, J = 7.4, 2H), 2.00–1.91 (m, 2H), 1.44 (s, 9H); ESI MS m/z 346 $[\text{M} + \text{H}]^+$.

Preparation of *S*-(5-(3-((*tert*-butoxycarbonyl)amino)propyl)pyrazin-2-yl)methyl ethanethioate (92**);**

A solution of **91** (210 mg, 0.608 mmol) in DMF (10 mL) was charged with KSAc (173 mg, 1.52 mmol) and stirred at room temperature for 2 h. The solvent was removed and the residue was partitioned between water (100.0 mL) and EtOAc (100 mL). The EtOAc layer was separated and the aqueous layer was extracted with EtOAc (2×100 mL). The combined organic layer was concentrated and the residue was purified by column chromatography to afford compound **92** (140 mg, 71% over two steps) as a yellow solid: ^1H NMR (300 MHz, CD_3Cl) δ 8.52 (s, 1H), 8.36 (s, 1H), 4.65 (br s, 1H), 4.22 (s, 2H), 3.21–3.15 (m, 2H), 2.82 (t, J = 7.4, 2H), 2.36 (s, 3H), 1.97–1.87 (m, 2H), 1.43 (s, 9H); ESI MS m/z 326 $[\text{M} + \text{H}]^+$.

Preparation of *S*-(5-(3-aminopropyl)pyrazin-2-yl)methyl ethanethioate hydrochloride (93**);**

Compound **92** (140 mg, 0.43 mmol) was dissolved in DCM (5 mL) followed by the addition of 4 N HCl in dioxane (2 mL) drop wise at room temperature, and the solution was stirred at same temperature for 2 h. After removal of the solvent, the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **93** (80 mg, 71%) as an hygroscopic off-white solid: ^1H NMR (300 MHz, CD_3OD) δ 8.62 (s, 1H), 8.51 (s, 1H), 4.27 (s, 2H), 3.04–2.92 (m, 4H), 2.35 (s, 3H), 2.12–2.07 (m, 2H);

^1H NMR (300 MHz, DMSO- d_6) δ 8.56 (s, 1H), 8.50 (s, 1H), 8.10 (br s, 3H), 4.24 (s, 2H), 2.87–2.78 (m, 4H), 2.36 (s, 3H), 2.03–1.90 (m, 2H); ESI MS m/z 226 $[\text{M} + \text{H}]^+$.

Preparation of (5-(3-aminopropyl)pyrazin-2-yl)methanethiol hydrochloride (34);

Compound **92** (600 mg, 1.84 mmol) was dissolved in methanol (5 mL) followed by the addition of 6 N HCl in isopropanol (30 mL) drop wise at room temperature, and the solution was stirred at same temperature for 12 h. After removal of the solvent, the residue was purified by reverse phase column chromatography to afford hydrochloric acid salt **94** (290 mg, 85%) as an hygroscopic blue-green gum: ^1H NMR (300 MHz, CD_3OD) δ 8.63 (s, 1H), 8.48 (s, 1H), 3.88 (s, 2H), 3.05–2.92 (m, 4H), 2.15–2.05 (m, 2H);

^1H NMR (300 MHz, DMSO- d_6) δ 8.61 (s, 1H), 8.48 (s, 1H), 7.93 (br s, 3H), 3.85 (d, $J = 8.0$ Hz, 2H), 3.03 (t, $J = 8.0$ Hz, 1H), 3.05–2.92 (m, 4H), 2.15–2.05 (m, 2H); ESI MS m/z 184 $[\text{M} + \text{H}]^+$.

DTNB ASSAY: Thiol-containing compounds, such as the monothiol mucolytic agents described in this patent, can react with DTNB (5,5-Dithiobis(2-nitrobenzoic acid)) resulting in the cleavage of its single S-S bond. The DTNB assay serves a dual purpose in our analysis of monothiol compounds, as it can (1) be used to determine the “active concentration” of the mucolytic compounds (what amount of the compound in a reaction is able to cleave S-S bonds) and (2) to assess the rate that the compound can cleave S-S bonds. When cleaved, the resulting compound, NTB (2-nitro-5-thiobenzoate), is a colored product that is measured spectrophotometrically at an absorbance of 412 nm (Abs_{412}). Using the molar extinction coefficient of NTB and measured maximum Abs_{412} , the molar amount of DTNB that reacted with our mucolytic agents can be calculated. Monothiol mucolytic compounds react at a 1:1 stoichiometric ratio with DTNB (*i.e.* 1 mole of NTB is produced when 1 mole of DTNB is reacted with 1 mole of a monothiol reducing agent). To define the activity concentration of a compound, a final concentration of 22.5 μM mucolytic reducing agent was combined with an excess of DTNB (100 μM) in 1 mL 50 mM Tris-HCl buffer (pH 7.5). Maximum Abs_{412} was measured and then utilized to calculate the activity concentration. If observed activity concentrations differed from expected activity concentrations by more than 5%, the amount of the compound added to each reaction was accordingly adjusted to kinetically test the reducing rate in the next step. To determine rate of mucolytic reducing activity, 22.5 μM active reducing agent is combined with 45 μM DTNB in 1 mL 50 mM Tris-HCl buffer over a

pH range (6.0-7.5). Abs_{412} is recorded in real time upon addition of the compound and rates were calculated using 2nd order kinetic parameters. Results are tabulated in Table 1.

Table 1. . Kinetic Reaction Rates of Reduction of DTNB by the Compounds of the present invention compared to NAC.

Compound	DTNB reduction rate (M-1 s-1)			
	pH 6	pH 6.5	pH 7	pH 7.5
NAC	10	26	69	230
76	253.2	654.24	1499	4633.8
69	485.93	-	-	-
86	160	-	-	-
48	190.8	-	-	-
47	211.3	-	-	-
19	182.52	-	-	-
58	258.31	-	-	-
20	307.08	-	-	-

PRO-DRUG DTNB ASSAY: This assay was designed to determine whether prodrug caps added on to our monothiol mucolytic compounds can be cleaved from the molecule. If so, the outcome would be an “active” compound that is able to reduce the S-S bond in DTNB. Similar to the activity concentration version of the DTNB assay described above, monothiol prodrugs were mixed at a final concentration of 22.5 μ M with excess DTNB (100 μ M final) in 1 mL 50 mM Tris-HCl buffer (pH 7.5) and maximum Abs_{412} was measured. In the absence of a purified hydrolytic enzyme (*e.g.* porcine liver esterase; Sigma), the amount of DTNB cleavage observed is an indicator for stability of the cap on the prodrug compound (*i.e.* if the prodrug remains intact in solution the $Abs_{412}=0$). Next, 5 μ L of esterase (bought as an ammonium sulfate suspension that is subsequently centrifuged to isolate the esterase and then dissolved in reaction buffer prior to assaying) is combined with excess DTNB (100 μ M final) and 22.5 μ M pro-drug in 1 mL 50 mM Tris-HCl buffer (pH 7.5). Cleavage of the prodrug cap can be visualized in real time via DTNB cleavage at Abs_{412} by the esterase-liberated monothiol molecule. Results are tabulated in Table 2.

Table 2. Reduction of Prodrugs with and without enzyme added.

Compound	Reduction Without Esterase	Reduction With Esterase
59	No	Yes
18	No	Yes
25	No	Yes
15a	No	Yes
10	No	Yes
85	No	Yes
17	No	Yes
24	No	Yes
14	No	Yes
9	No	Yes
46	No	Yes

PARALLEL ARTIFICIAL MEMBRANE PERMEABILITY (PAMPA) ASSAY: This assay measures the permeability of small molecules across an artificial phospholipid membrane to help predict *in vivo* drug permeability. First, 500 μ M stock solutions were made up in PBS and tested by the DTNB assay (described above) to determine compound activity concentrations. Next, 300 μ L of the 500 μ M compound stock solution and 200 μ L PBS were added per well to the donor and acceptor plates, respectively (BD Gentest™ Pre-Coated PAMPA Plate System). The acceptor plate was then placed on top of the donor plate and allowed to incubate at room temperature for 5 hours. After incubation, the donor and acceptor plates were separated. For each reaction, samples were taken from both the acceptor and donor plates and were combined with DTNB prior to reading spectrophotometrically (maximum Abs₄₁₂). For prodrug samples, 1 μ L of purified esterase (porcine liver esterase; Sigma) was added per well and the samples were incubated at room temperature for 5 minutes to allow for cleavage of the pro-drug cap prior to addition of DTNB. Using the concentrations of compound identified in both the donor and acceptor plates for each sample, a compound permeability parameter was calculated following equations outlined in the BD Gentest™ Pre-Coated PAMPA Plate System Manual.

MUCIN AGAROSE GEL WESTERN BLOTS: Various mucin-containing substrates (*e.g.* saliva, harvested HBE mucus, and disease sputum) treated with our monothiol mucolytic compounds are quenched upon completion of the treatment period with a 10-fold excess of N-ethylmaleimide in order to alkylate any remaining active compound and to prevent further mucin reduction. A 10x concentrated sample loading buffer is diluted into each sample (1x TAE/5% glycerol/0.1% SDS/Bromophenol Blue). Samples (50 µg) were analyzed by electrophoresis on 0.9% agarose gels using a buffer system consisting of 1x TAE/0.1% SDS. The agarose gel was soaked for 15 min in 4xSSC (0.6 M NaCl, 60 mM Tri-sodium citrate dehydrate) containing 10 mM DTT before transferring the samples from the gel onto a nitrocellulose membrane by vacuum blotter. Unreduced and reduced Muc5B were visualized on a LiCor Odyssey imaging detection system using a polyclonal antibody directed towards Muc5B.

BiP INDUCTION: Reducing agents were made up in 50 mM Tris-HCl buffered to pH 7.5. Each compound solution (15 µL of 10 mM compound) was added to the apical surface of primary HBEs for 24 hrs. The cells were then lysed in RIPA buffer (50 mM Tris-HCl (pH 8.0)/150 mM NaCl/1.0% NP-40/0.5% sodium deoxycholate/0.1% SDS) supplemented with protease inhibitor cocktail (Roche) and 1 mM phenylmethylsulfonyl fluoride. The samples were normalized to contain the same total amount of protein followed by addition of 2X SDS sample buffer (100 mM Tris-HCl (pH 6.8)/4% SDS/0.05% Bromophenol Blue/20% glycerol). Samples (20 µg) were analyzed by electrophoresis on a 10% SDS-PAGE gel and transferred to a nitrocellulose membrane. BiP levels were visualized using a polyclonal antibody directed towards BiP and the LiCor Odyssey imaging detection system. Thapsigargin (TG, 2.5 µM) and DTT serve as a positive control for BiP induction.

IL-8 SECRETION: Reducing agents were made up in 50 mM Tris-HCl buffered to pH 7.5. Each compound solution (15 µL of 10 mM compound) was added to the apical surface of primary HBEs.

IL-8 secretion was measured from the basolateral HBE media 24 hours post-dose using a ThermoScientific human IL-8 ELISA kit. Samples were diluted 1:50 and then 50 µL of each dilution was added to the ELISA plate. The samples were completed in duplicate following standard reaction conditions as outlined in the kit manual. Absorbance was measured at 450 nm. A standard curve, generated from standards with known amounts of human IL-8, was used to calculate IL-8 amounts in the unknown samples. Supernatant from mucopurulent

matters (SMM) purified from cystic fibrosis sputum was used as a positive control for IL-8 secretion.

Data using these assays is compiled in Figures 2-9 and is discussed in detail as follows:

As shown in Figure 2, enhanced mucin reducing capabilities of compound **76** relative to NAC are provided. The novel mucolytic agents incorporate several features to produce therapeutic agents with favorable properties relative to currently available agents. One limitation of NAC, the only approved mucolytic for inhalation, is its very slow reducing kinetics, requiring both very high drug concentrations and long incubation times. Compound **76**, a novel mucolytic warhead, demonstrates significantly enhanced kinetics relative to NAC. As shown by agarose gel western blot, **76** at equimolar concentrations relative to NAC (50 mM) produces a significantly faster and more complete reduction of salivary Muc5b compared to NAC. Furthermore, **76** produces greater Muc5b reduction relative to NAC at a 5-fold lower concentration (10 mM). Thus, **76** exhibits properties of a more active reducing agent compared to NAC.

As shown in Figure 3, modification of Compound **76** can be accomplished without loss of reducing activity. The functional substitutions of **76**, as illustrated by the derivatives **86**, **69**, and **47**, retain the reducing capacity of **76**. As shown in the figure, all compounds are significantly more active than NAC at reducing Muc5B (as indicated by the loss of the high molecular weight Muc5b band on the western blot).

In Figure 4, the reducing activity of Compound **86** relative to compounds known in the art. By agarose gel western blot, **86** demonstrates superior Muc5b reducing activity relative to NAC and another agent known in the art (compound **95** described in WO2014153009). Only **86** produces full Muc5b reduction at 30 mM and partial reduction at 3 mM; whereas the other compounds only produce partial Muc5b reduction at the highest concentration tested (30 mM).

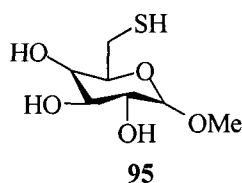


Figure 5 shows the advantage of compound **76** substitutions. A primary limitation of NAC as a pulmonary mucolytic agent is limited airway surface drug retention (the Mucomyst product insert describes a pulmonary surface half-life of 20 minutes). As shown in the figure

the **76** warhead is relatively lipophilic and membrane permeable as measured using the PAMPA assay. However, substituted **76** molecules, such as **86** and **85** (which retain the enhanced activity of **76** relative to NAC), are more polar and less lipophilic, resulting in poor membrane permeability. Thus, the data predict that **86** and **85** will favorably exhibit enhanced compound retention on the lung surface.

Figure 6 shows integrated assays to assess cell permeation and pro-inflammatory effects. Compounds were incubated on the apical surface of polarized HBE cells for 24 hours at 10 mM and the induction of the (A) BiP protein or (B) IL-8 secretion was measured. Induction of the BiP protein is a marker for endoplasmic reticulum (ER) stress, which can be caused by the inhibition of disulfide bond formation during protein synthesis. As **86** was predicted to poorly permeate cells, it was expected that this compound would not reach the ER and, therefore, not induce BiP expression. **Panel A:** **86** and **69** do not induce BiP expression relative to vehicle controls (dashed line), whereas a permeable reducing agent (DTT) and thapsigargin (TG) do. Thus the data indicate that **86** and **69** are not significantly internalized in the cell when added to the apical compartment. **Panel B:** To assess the potential pro-inflammatory properties of the compounds, IL-8 secretion was measured following the 24 hour compound incubation. Significantly, **86** did not produce any evidence of pro-inflammatory effects as evidenced by no change in IL-8. However, **69** did increase IL-8 secretion, along with a positive control (SMM). As **86** and **69** share a common warhead, **76**, which did not increase IL-8 secretion, we conclude that the substitutions on **69**, but not **86**, are responsible for this effect.

Figure 7 shows pro-drugs of **86**. **85** is the thio-acetate derivative of **86**. Importantly, the pro-drug moiety renders **85** odorless and inactive (until the compound is metabolically activated). The figure shows **86** in the DTNB assay, which rapidly cleaves DTNB (left panel). Conversely **85** does not cleave DTNB (middle panel), demonstrating that the compound is inactive. However, the addition of an esterase metabolically converts **85** to **86**, allowing it to hydrolyze DTNB (right-hand panel).

Figure 8 shows the metabolic activation of **85** in COPD sputum. An important aspect of mucolytic pro-drugs is that they must be activated in mucus on the lung surface. To evaluate the metabolic activation and kinetics, **86**(active metabolite) and **85** (pro-drug) were incubated from spontaneously induced sputum from a patient with COPD. As shown in the figure, **86** rapidly reduced Muc5b in the sputum as assessed by agarose gel western blot. **85** likewise reduces the Muc5b, but with a delayed kinetic relative to **86** (which reflects the requirement for enzymatic metabolism of **85** to **86**). Importantly, these data demonstrate the

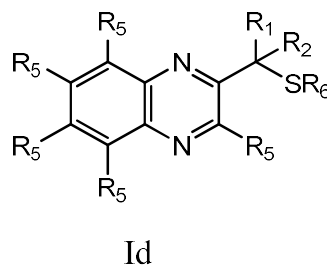
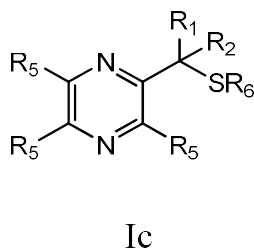
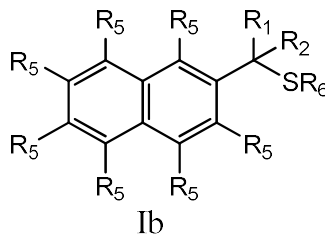
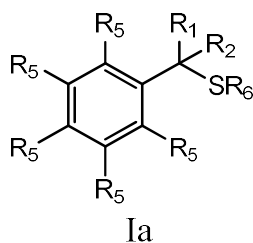
human sputum contains the enzymes required to activate compounds containing thioesters, such as **85**.

Figure 9 shows the mucus reduction on primary human bronchial epithelial (HBE) cultures. Mucin reduction kinetics were assessed by western blot at the indicated times post-addition of mucolytic agents to the apical surface of HBE cultures. **86** produces a rapid reduction of the mucus that is substantially recovered 24 hours after dosing. **85** exhibits slower reduction kinetics (e.g. 1-2 hours), but a potentially longer duration of action (e.g. 24 hours). Importantly, the data demonstrate that human airway epithelia with mucus can metabolize the **85** pro-drug to the active **86** mucolytic agent.

Each of the references cited above throughout this application are incorporated herein by reference. In the event of a conflict between the foregoing description and a reference, the description provided herein controls.

CLAIMS

1. A compound represented by formula (Ia)-(Id):

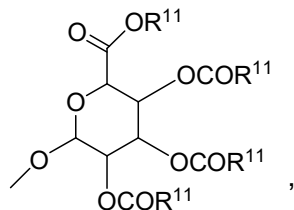
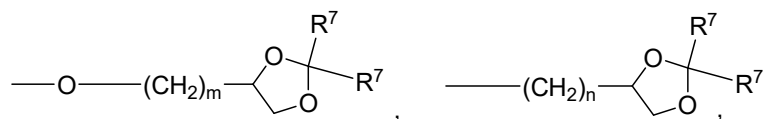


wherein

R^1 and R^2 are each, independently, hydrogen, lower alkyl, halogen, trifluoromethyl, hydroxyl-lower alkyl, phenyl, (phenyl)-lower alkyl, (halophenyl)-lower alkyl, ((lower-alkyl)phenyl)-lower-alkyl, ((lower-alkoxy)phenyl)-lower-alkyl, (naphthyl)-lower-alkyl, or (pyridyl)-lower-alkyl;

R^3 and R^4 are each, independently, hydrogen, lower alkyl, hydroxyl-lower alkyl, phenyl, (phenyl)-lower alkyl, (halophenyl)-lower alkyl, ((lower-alkyl)phenyl)-lower-alkyl, ((lower-alkoxy)phenyl)-lower-alkyl, (naphthyl)-lower-alkyl, or (pyridyl)-lower-alkyl;

each R^5 is, independently, hydrogen, halogen, trifluoromethyl, lower alkyl, unsubstituted or substituted phenyl, lower alkyl-thio, phenyl-lower alkyl-thio, lower alkyl-sulfonyl, or phenyl-lower alkyl-sulfonyl, OH, $-(CH_2)_m-OR^8$, $-O-(CH_2)_m-OR^8$, $-O-(CH_2)_m-NR^7R^{10}$, $-O-(CH_2)_m-NR^7R^7$, $-O-(CH_2)_m-NR^{10}R^{10}$, $-(CH_2)_n(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-O-(CH_2)_m(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-(CH_2CH_2O)_m-R^8$, $-O-(CH_2CH_2O)_m-R^8$, $-(CH_2CH_2O)_m-CH_2CH_2NR^7R^{10}$, $-O-(CH_2CH_2O)_m-CH_2CH_2NR^7R^{10}$, $-(CH_2)_n-C(=O)NR^7R^{10}$, $-O-(CH_2)_m-C(=O)NR^7R^{10}$, $-(CH_2)_n-(Z)_g-R^7$, $-O-(CH_2)_m-(Z)_g-R^7$, $-(CH_2)_n-NR^{10}-CH_2(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-O-(CH_2)_m-NR^{10}-CH_2(CHOR^8)(CHOR^8)_n-CH_2OR^8$, $-(CH_2)_n-CO_2R^7$, $-O-(CH_2)_m-CO_2R^7$, $-OSO_3H$, $-O$ -glucuronide, $-O$ -glucose,



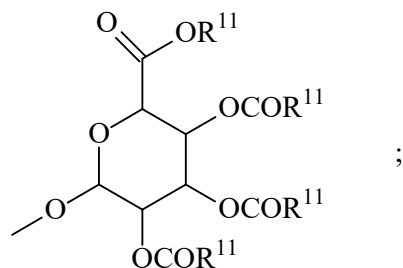
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with the proviso that at least one R⁵ group contains at least one basic nitrogen;

each R⁶ is, independently, hydrogen, -C(=O)-R⁷, or an amino acyl of the natural configuration;

each R⁷ is, independently, hydrogen, lower alkyl, phenyl, substituted phenyl, lower alkyl phenyl, -CH₂(CHOR⁸)_m-CH₂OR⁸; 2-furyl or 3-furyl;

each R⁸ is, independently, hydrogen, lower alkyl, lower alkyl phenyl, -C(=O)-R¹¹, glucuronide, 2-tetrahydropyranyl, or



each R⁹ is, independently, -CO₂R⁷, -CON(R⁷)₂, -SO₂CH₃, -C(=O)R⁷, -CO₂R¹³, -CON(R¹³)₂, -SO₂CH₂R¹³, or -C(=O)R¹³;

each R¹⁰ is, independently, -H, -SO₂CH₃, -CO₂R⁷, -C(=O)-NR⁷R⁹, -C(=O)R⁷, or -CH₂-(CHOH)_n-CH₂OH;

each Z is, independently, $-(\text{CHOH})-$, $-\text{C}(=\text{O})-$, $-(\text{CHNR}^7\text{R}^{10})-$, $-(\text{C}=\text{NR}^{10})-$, $-(\text{CH}_2)_n-$, $-(\text{CHNR}^{13}\text{R}^{13})-$, $-(\text{C}=\text{NR}^{13})-$, or $-\text{CO}_2\text{H}$;

each R^{11} is, independently, hydrogen, lower alkyl, phenyl lower alkyl or substituted phenyl lower alkyl;

each R^{13} is, independently, hydrogen, lower alkyl, phenyl, substituted phenyl or $-\text{CH}_2(\text{CHOR}^8)_m-\text{CH}_2\text{OR}^8$, $-\text{SO}_2\text{CH}_3$, $-\text{CO}_2\text{R}^7$, $-\text{C}(=\text{O})\text{NR}^7\text{R}^9$, $-\text{C}(=\text{O})\text{R}^7$, $-\text{CH}_2-(\text{CHOH})_n-\text{CH}_2\text{OH}$, $-(\text{CH}_2)_m-\text{NR}^7\text{R}^{10}$, $-(\text{CH}_2)_m-\text{NR}^7\text{R}^7$, $-(\text{CH}_2)_m-\text{NR}^{11}\text{R}^{11}$, $-(\text{CH}_2)_m-(\text{NR}^{11}\text{R}^{11}\text{R}^{11})^+$, $-(\text{CH}_2)_m-(\text{CHOR}^8)_m-(\text{CH}_2)_m\text{NR}^{11}\text{R}^{11}$, $-(\text{CH}_2)_m-(\text{CHOR}^8)_m-(\text{CH}_2)_m\text{NR}^7\text{R}^{10}$, $-(\text{CH}_2)_m-\text{NR}^{10}\text{R}^{10}$, $-(\text{CH}_2)_m-(\text{CHOR}^8)_m-(\text{CH}_2)_m-(\text{NR}^{11}\text{R}^{11}\text{R}^{11})^+$, $-(\text{CH}_2)_m-(\text{CHOR}^8)_m-(\text{CH}_2)_m\text{NR}^7\text{R}^7$;

each g is, independently, an integer from 1 to 6;

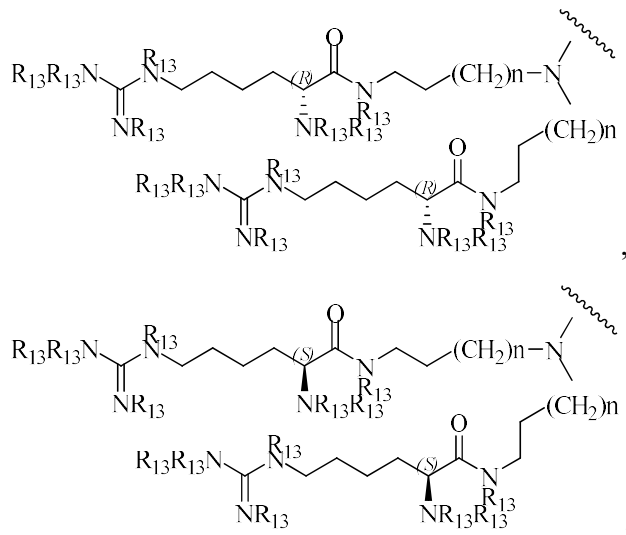
each m is, independently, an integer from 1 to 7;

each n is, independently, an integer from 0 to 7;

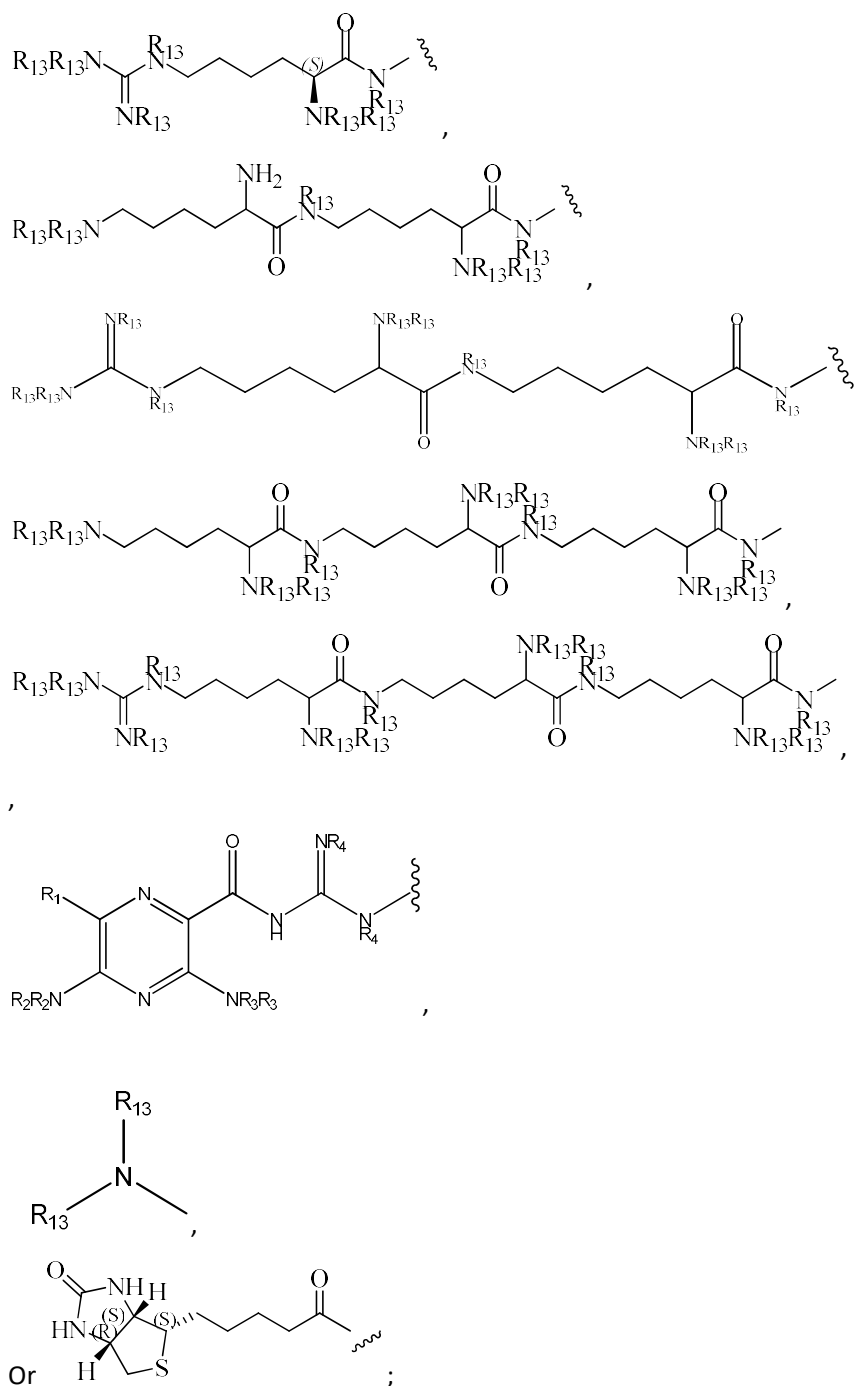
each $-\text{Het}-$ is, independently, $-\text{N}(\text{R}^7)-$, $-\text{N}(\text{R}^{10})-$, $-\text{S}-$, $-\text{SO}-$, $-\text{SO}_2-$, $-\text{O}-$, $-\text{SO}_2\text{NH}-$, $-\text{NHSO}_2-$, $-\text{NR}^7\text{CO}-$, $-\text{CONR}^7-$, $-\text{N}(\text{R}^{13})-$, $-\text{SO}_2\text{NR}^{13}-$, $-\text{NR}^{13}\text{CO}-$, or $-\text{CONR}^{13}-$;

each Link is, independently, $-\text{O}-$, $-(\text{CH}_2)_n-$, $-\text{O}(\text{CH}_2)_m-$, $-\text{NR}^{13}-\text{C}(=\text{O})-\text{NR}^{13}-$, $-\text{NR}^{13}-\text{C}(=\text{O})-(\text{CH}_2)_m-$, $-\text{C}(=\text{O})\text{NR}^{13}-(\text{CH}_2)_m-$, $-(\text{CH}_2)_n-(\text{Z})_g-(\text{CH}_2)_n-$, $-\text{S}-$, $-\text{SO}-$, $-\text{SO}_2-$, $-\text{SO}_2\text{NR}^7-$, $-\text{SO}_2\text{NR}^{10}-$, or $-\text{Het}-$;

each CAP is, independently







with the proviso that when any $-CHOR^8$ - or $-CH_2OR^8$ groups are located 1,2- or 1,3- with respect to each other, the R^8 groups may, optionally, be taken together to form a cyclic mono- or di-substituted 1,3-dioxane or 1,3-dioxolane;

and racemates, enantiomers, diastereomers, tautomers, polymorphs, pseudopolymorphs and pharmaceutically acceptable salts, thereof.

2. A non-therapeutic use of the compound of claim 1 to liquefy mucus from mucosal surfaces, wherein the compound is to be administered to a mucosal surface of a subject.

3. A non-therapeutic use of the compound of claim 1 to promote any one or more of the following conditions: ocular hydration, corneal hydration, and mucus clearance in mucosal surfaces, or to induce sputum for diagnostic purposes.

4. The compound of claim 1 for use in therapy.

5. The compound of claim 1 for use in the treatment of any one or more of the following conditions: chronic bronchitis, bronchiectasis, cystic fibrosis, chronic obstructive pulmonary disease, asthma, pulmonary fibrosis, sinusitis, vaginal dryness, dry eye, Sjogren's disease, distal intestinal obstruction syndrome, esophagitis, dry mouth, ventilator-induced pneumonia, asthma primary ciliary dyskinesia, otitis media, cystinosis, emphysema, pneumonia, constipation, chronic diverticulitis and rhinosinusitis.

6. The compound of claim 1 for use in the treatment of an eye disease characterized by the presence of ocular discharge.

7. The compound of claim 6, wherein the eye disease is one or more conditions selected from the group consisting of blepharitis, allergies, conjunctivitis, corneal ulcer, trachoma, congenital herpes simplex, corneal abrasions, ectropion, eyelid disorders, gonococcal conjunctivitis, herpetic keratitis, ophthalmitis, Sjogren's Syndrome, Stevens-Johnson Syndrome.

8. The compound of claim 1 and an osmolyte for use in the treatment of a disease ameliorated by increased mucociliary clearance and mucosal hydration.

9. Use of the compound of claim 1 in the manufacture of a medicament for the treatment of any one or more of the following conditions: chronic bronchitis, bronchiectasis, cystic fibrosis, chronic obstructive pulmonary disease, asthma, pulmonary fibrosis, sinusitis, vaginal dryness, dry eye, Sjogren's disease, distal intestinal obstruction syndrome, esophagitis, dry mouth, ventilator-induced pneumonia, asthma, primary ciliary dyskinesia,

otitis media, cystinosis, emphysema, pneumonia, constipation, chronic diverticulitis and rhinosinusitis.

10. Use of the compound of claim 1 in the manufacture of a medicament for the treatment of an eye disease characterized by the presence of ocular discharge.

11. Use according to claim 10, wherein the eye disease is one or more conditions selected from the group consisting of blepharitis, allergies, conjunctivitis, corneal ulcer, trachoma, congenital herpes simplex, corneal abrasions, ectropion, eyelid disorders, gonococcal conjunctivitis, herpetic keratitis, ophthalmitis, Sjogren's Syndrome, Stevens-Johnson Syndrome.

12. Use of the compound of claim 1 and an osmolyte in the manufacture of a medicament for the treatment of a disease ameliorated by increased mucociliary clearance and mucosal hydration, wherein the disease is one or more conditions selected from the group consisting of chronic bronchitis, bronchiectasis, pulmonary fibrosis, cystic fibrosis, asthma, sinusitis, vaginal dryness, dry eye, Sjogren's disease, distal intestinal obstruction syndrome, esophagitis, dry mouth (xerostomia), asthma, primary ciliary dyskinesia, otitis media, chronic obstructive pulmonary disease, emphysema, pneumonia, diverticulitis, rhinosinusitis, and airborne infections.

13. The compound of claim 1 and an osmolyte for use according to claim 8, wherein the disease is one or more conditions selected from the group consisting of chronic bronchitis, bronchiectasis, pulmonary fibrosis, cystic fibrosis, asthma, sinusitis, vaginal dryness, dry eye, Sjogren's disease, distal intestinal obstruction syndrome, esophagitis, dry mouth (xerostomia), asthma, primary ciliary dyskinesia, otitis media, chronic obstructive pulmonary disease, emphysema, pneumonia, diverticulitis, rhinosinusitis, and airborne infections.

14. The compound of claim 1 and an osmolyte for use according to claim 8, or the use of claim 12, wherein the compound is to be administered preceding administration of the osmolyte.

15. The compound of claim 1 and an osmolyte for use according to claim 8, or the use of claim 12, wherein the compound is to be administered concurrent with administration of the osmolyte.

16. The compound of claim 1 and an osmolyte for use according to claim 8, or the use of claim 12, wherein the compound is to be administered following administration of the osmolyte.

17. The compound of claim 1 and an osmolyte for use according to claim 8, or the use of claim 12, wherein the osmolyte is hypertonic saline or mannitol.

18. The compound of claim 1 and an osmolyte for use according to claim 8, or the use of claim 12, wherein the osmolyte is sodium chloride which is delivered as a micronized particle of respirable size.

19. The compound of claim 1 and an osmolyte for use according to claim 8, or the use of claim 12, wherein the osmolyte and a compound of formula (Ia)-(Id) is to be administered by aerosolization using a device capable of delivering the formulation to the nasal passages or pulmonary airway wherein the aerosol is a respirable size.

20. A composition, comprising:

(a) the compound of claim 1 and (b) an osmotically active compound.

21. A non-therapeutic use of the compound of claim 1 and an osmolyte to induce sputum in a subject in need of increased mucociliary clearance and mucosal hydration.

22. The compound of claim 1 and an osmolyte for use in therapy.

23. The compound of claim 1 for use in the prophylactic, post-exposure prophylactic, preventive or therapeutic treatment against diseases or conditions caused by a pathogen, in a subject in need of increased mucociliary clearance and mucosal hydration.

24. The compound of claim 23, wherein the pathogen is anthrax or plague.

25. Use of the compound of claim 1 in the manufacture of a medicament for the prophylactic, post-exposure prophylactic, preventive or therapeutic treatment against diseases or conditions caused by a pathogen, in a subject in need of increased mucociliary clearance and mucosal hydration, wherein the pathogen is anthrax or plague.

26. The compound of claim 1, or a pharmaceutically acceptable salt thereof, for use in the prevention, mitigation, and/or treatment of deterministic health effects to the respiratory tract and/or other bodily organs caused by respirable aerosols containing radionuclides in a human in need thereof.

27. Use of the compound of claim 1, or a pharmaceutically acceptable salt thereof, in the manufacture of a medicament for the prevention, mitigation, and/or treatment of deterministic health effects to the respiratory tract and/or other bodily organs caused by respirable aerosols containing radionuclides in a human in need thereof.

28. A pharmaceutical composition, comprising the compound of claim 1 and a pharmaceutically acceptable carrier.

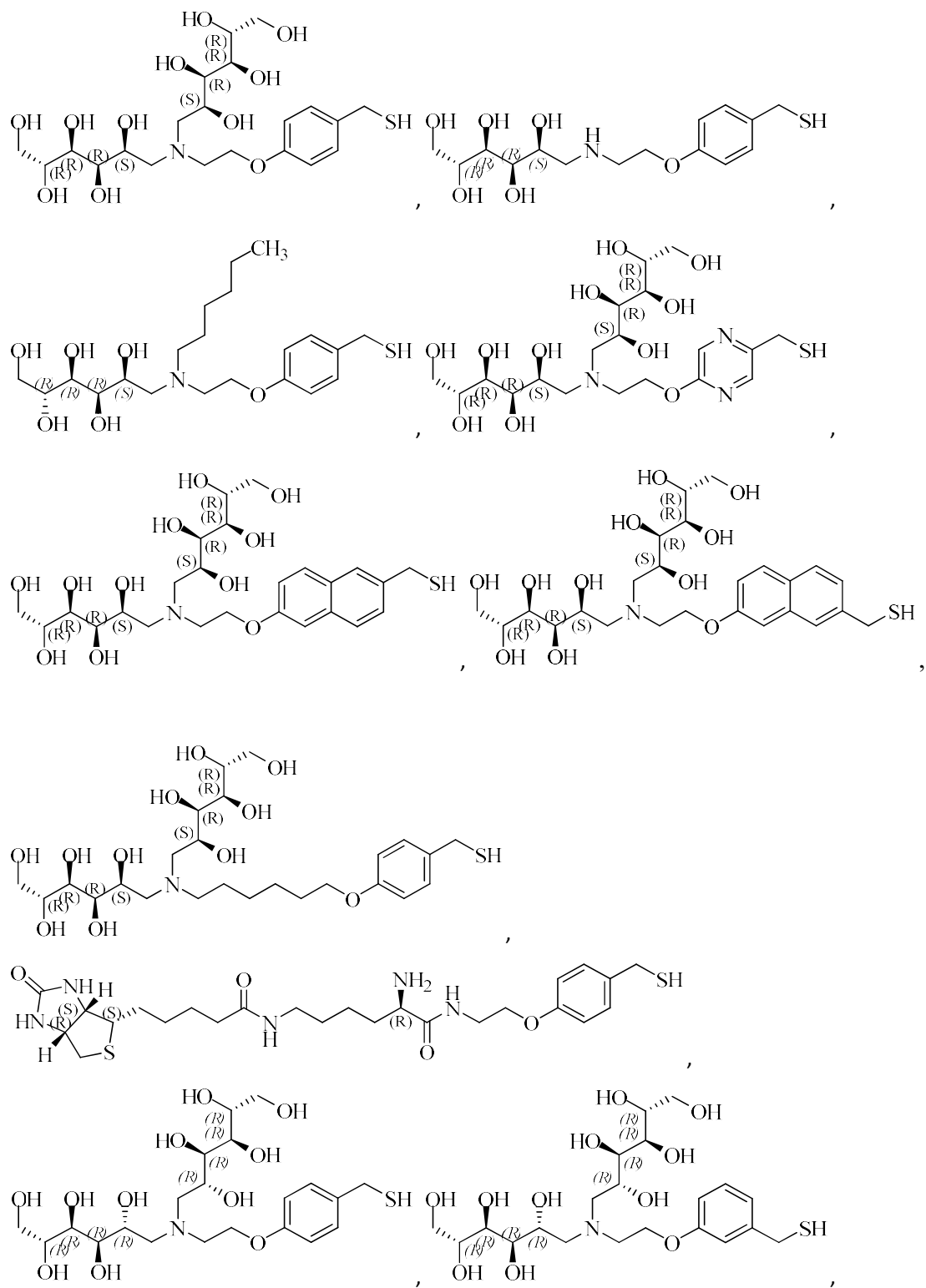
29. The compound of claim 1 and a second therapeutic agent for use in improving mucus penetration of therapeutic agents.

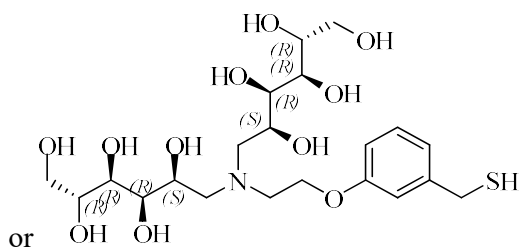
30. The compound of claim 1 and a second therapeutic agent for use according to claim 29, wherein the therapeutic agents is an osmolyte, a sodium channel blocker, a secretagogue, a bronchodilator, an anti-infective, an anti-inflammatory, or a gene carrier.

31. A non-therapeutic use of the compound of claim 1 to decrease mucosal oxygen free radicals.

32. The compound of claim 1 for use in decreasing mucosal oxygen free radicals.

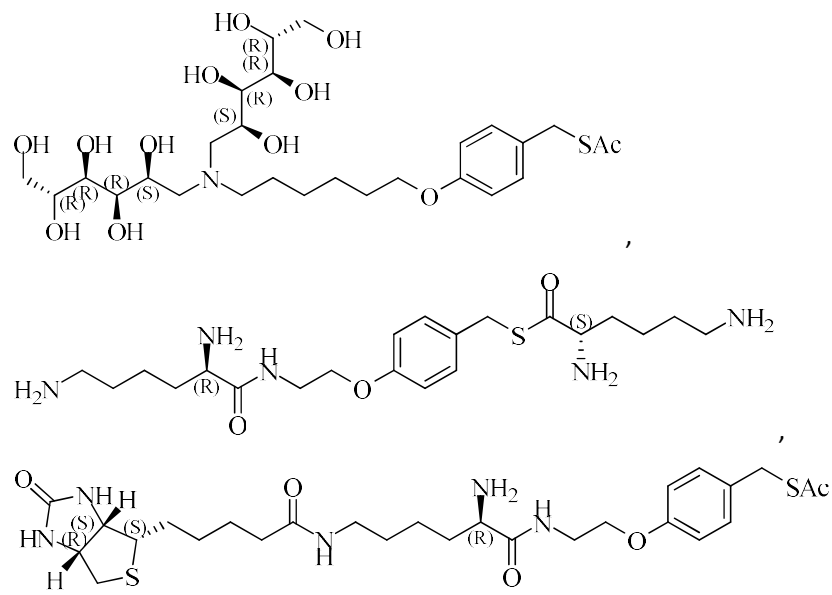
33. The compound of claim 1, which is represented by the formula:

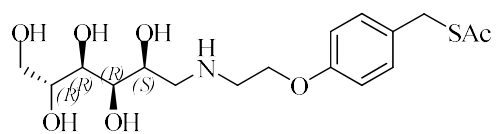




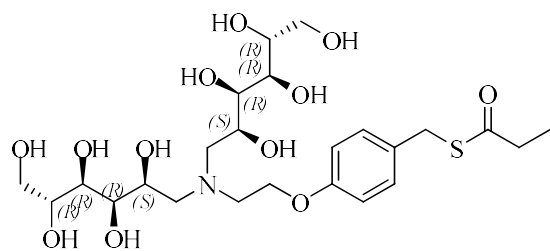
34. The compound of claim 1, which is an acid addition salt of an inorganic acid or an organic acid selected from the group consisting of hydrochloric acid, hydrobromic acid, sulfuric acid, phosphoric acid, nitric acid, acetic acid, oxalic acid, tartaric acid, succinic acid, maleic acid, fumaric acid, gluconic acid, citric acid, malic acid, ascorbic acid, benzoic acid, tannic acid, palmitic acid, alginic acid, polyglutamic acid, naphthalensulfonic acid, methanesulfonic acid, p-toluenesulfonic acid, naphthalenedisulfonic acid, polygalacturonic acid, malonic acid, sulfosalicylic acid, glycolic acid, 2-hydroxy-3-naphthoate, pamoate, salicylic acid, stearic acid, phthalic acid, mandelic acid, and lactic acid.

35. A prodrug compound represented by the formula:

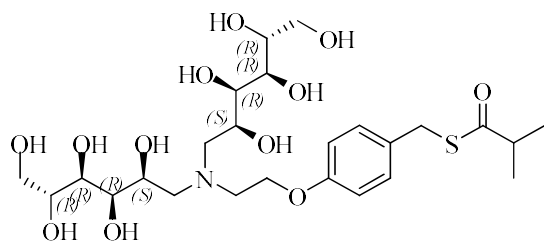




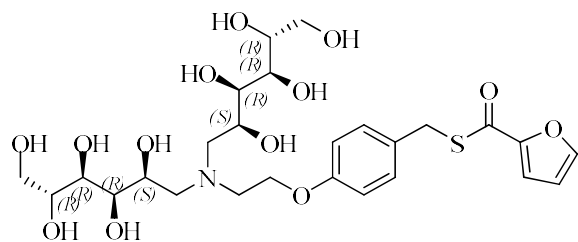
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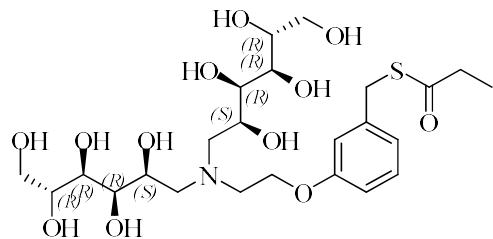
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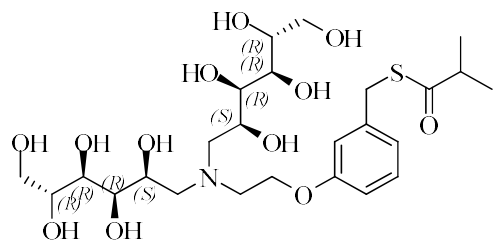
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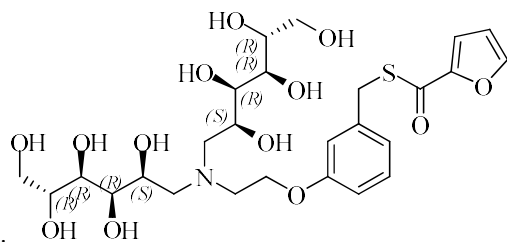
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