METHODS FOR PURIFICATION OF MESSENGER RNA

CROSS REFERENCE TO RELATED APPLICATION

[0001] This patent application claims the benefit of United States Provisional Patent Application serial number 61/784,996, filed March 14, 2013, the entirety of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] Messenger RNA therapy is becoming an increasingly important approach for the treatment of a variety of diseases. Messenger RNA therapy involves administration of messenger RNA (mRNA) into a patient in need of the therapy and production of the protein encoded by the mRNA within the patient body. Thus, it is important to ensure the production of highly pure and safe mRNA product. Traditionally, RNA purification typically employs spin columns and involves the use of caustic or flammable solvents, such as ethanol, which is undesirable for therapeutic administration and large scale production.

SUMMARY OF THE INVENTION

[0003] The present invention provides improved methods of purifying mRNA that is suitable for administration as a pharmaceutical product based on tangential flow filtration (TFF). Prior to the present invention, RNA purification typically employs spin columns and involves the use of caustic or flammable solvents, such as ethanol, which is undesirable for therapeutic administration and large scale production. Further, the prior art method typically does not allow for the separation of incomplete transcripts known as premature aborts or "shortmers," which is reported to be highly immunostimulatory and the presence of which may greatly alter the toxicity and tolerability profile of mRNA as active pharmaceutical ingredient (API). The present invention is, in part, based on the discovery that tangential flow filtration is surprisingly effective

to remove reactants, enzymes, by products, in particular, the shortmers, from mRNA production mixture. As described herein, tangential flow filtration, particularly in combination with a pre-treatment using a denaturing agent, can effectively remove reactants, enzymes and byproducts including prematurely aborted RNA sequences (i.e., shortmers), while still maintaining the integrity of mRNA. More surprisingly, the present inventors have demonstrated that tangential flow filtration can be successfully performed using only aqueous buffers as solvents without using any caustic or flammable solvents. Thus, the present invention provides a more effective, reliable, and safer method of purifying mRNA from large scale manufacturing process therapeutic applications.

[0004] In one aspect, the present invention provides, among other things, methods of purifying messenger RNA (mRNA) including the steps of (a) subjecting an impure preparation comprising *in vitro* synthesized mRNA to a denaturing condition, and (b) purifying the mRNA from the impure preparation from step (a) by tangential flow filtration, wherein the mRNA purified from step (b) is substantially free of prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis.

[0005] In some embodiments, step (a) comprises adding a protein denaturing agent to the impure preparation. In some embodiments, step (a) comprises incubating the impure preparation with the protein denaturing agent added at room temperature for about 1-10 minutes (e.g., about 2-9, 2-8, 2-7, 3-10, 3-9, 3-8, 3-7, 3-6, 4-10, 4-9, 4-8, 4-7, 4-6 minutes). In some embodiments, step (a) comprises incubating the impure preparation with the protein denaturing agent added at room temperature for about 1,2, 3, 4, 5, 6, 7, 8, 9, or 10 minutes. In some embodiments, step (a) comprises incubating the impure preparation with the protein denaturing agent added at room temperature for about 5 minutes. In some embodiments, a suitable protein denaturing agent is selected from the group consisting of urea, guanidinium thiocyanate, KCl, sodium dodecyl sulfate, sarcosyl, other detergents, and combinations thereof.

[0006] In some embodiments, step (a) comprises adding urea to the impure preparation to achieve a resulting urea concentration of about 1 M or greater. In some embodiments, the resulting urea concentration is about 2 M or greater, 3 M or greater, 4 M or greater, 5 M or greater, 6 M or greater, 7 M or greater, 8 M or greater, 9 M or greater, or 10 M or greater.

[0007] In some embodiments, step (a) comprises adding guanidinium thiocyanate to the impure preparation to achieve a resulting guanidinium thiocyanate concentration of about 1 M or greater. In some embodiments, the resulting guanidinium thiocyanate concentration is about 2 M or greater, 3 M or greater, 4 M or greater, 5 M or greater, 6 M or greater, 7 M or greater, 8 M or greater, 9 M or greater, or 10 M or greater.

[0008] In some embodiments, step (a) comprises adding KCl to the impure preparation to achieve a resulting KCl concentration of about 1 M or greater. In some embodiments, the resulting KCl concentration is about 2 M or greater, 3 M or greater, 4 M or greater, or 5 M or greater.

[0009] In some embodiments, the tangential flow filtration is performed using only aqueous solvents. In some embodiments, the tangential flow filtration is performed using water as solvent. In some embodiments, the tangential flow filtration is performed at a feed rate of approximately 100-200 mL/minute (e.g., approximately 100-180 mL/minute, 100-160 mL/minute, 100-140 mL/minute, 110-190 mL/minute, 110-170 mL/minute, or 110-150 mL/minute) and/or a flow rate of approximately 10-50 mL/minute (e.g., approximately 10-40 mL/minute, 10-30 mL/minute, 20-50 mL/minute, or 20-40 mL/minute). In some embodiments, the tangential flow filtration is performed at a feed rate of approximately 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, or 200 mL/minute and/or a flow rate of approximately 10, 20, 30, 40, or 50 mL/minute.

[0010] In some embodiments, the mRNA purified from step (b) contains less than about 5% (e.g., less than about 4%, 3%, 2%, or 1%) of prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis. In some embodiments, the mRNA purified from step (b) contains less than about 1% (e.g., less than about 0.9%, 0.8%, 0.7%, 0.6%, 0.5%, 0.4%, 0.3%, 0.2%, or 0.1%) of prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis. In some embodiments, the mRNA purified from step (b) contains less than 0.5% of prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis. In some embodiments, the mRNA purified from step (b) contains less than 0.1% of prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis. In some embodiments, the mRNA purified from step (b) contains undetectable prematurely aborted RNA

sequences and/or enzyme reagents used in *in vitro* synthesis as determined by eithidium bromide and/or Coomassie staining.

[0011] In some embodiments, the prematurely aborted RNA sequences comprise less than 15 bases (e.g., less than 14, 13, 12, 11, 10, 9 or 8 bases). In some embodiments, the prematurely aborted RNA sequences comprise about 8-12 bases.

[0012] In some embodiments, the enzyme reagents used in *in vitro* synthesis comprise T7 RNA polymerase, DNAse I, pyrophosphatase, and/or RNAse inhibitor. In some embodiments, the enzyme reagents used in *in vitro* synthesis comprise T7 RNA polymerase.

[0013] In some embodiments, the tangential flow filtration is performed before a cap and poly-A tail are added to the *in vitro* synthesized mRNA. In some embodiments, the tangential flow filtration is performed after a cap and poly-A tail are added to the *in vitro* synthesized mRNA. In some embodiments, the tangential flow filtration is performed both before and after a cap and poly-A tail are added to the *in vitro* synthesized mRNA.

[0014] In some embodiments, the *in vitro* synthesized mRNA is greater than about 1 kb, 1.5 kb, 2 kb, 2.5 kb, 3 kb, 3.5 kb, 4 kb, 4.5 kb, or 5 kb in length. In some embodiments, the *in vitro* synthesized mRNA comprises one or more modifications to enhance stability. In some embodiments, the one or more modifications are selected from modified nucleotide, modified sugar phosphate backbones, 5' and/or 3' untranslated region. In some embodiments, the *in vitro* synthesized mRNA is unmodified.

[0015] In some embodiments, the mRNA purified from step (b) has an integrity greater than about 95% (e.g., greater than about 96%, 97%, 98%, 99% or more). In some embodiments, the mRNA purified from step (b) has an integrity greater than 98%. In some embodiments, the mRNA purified from step (b) has an integrity greater than 99%. In some embodiments, the mRNA purified from step (b) has an integrity of approximately 100%.

[0016] The present invention also provides methods for manufacturing messenger RNA (mRNA) including the steps of synthesizing mRNA *in vitro*, and purifying the *in vitro* synthesized mRNA according to methods described herein.

[0017] The present invention also provides messenger RNA (mRNA) purified according to the methods described herein.

[0018] As used in this application, the terms "about" and "approximately" are used as equivalents. Any numerals used in this application with or without about/approximately are meant to cover any normal fluctuations appreciated by one of ordinary skill in the relevant art.

[0019] Other features, objects, and advantages of the present invention are apparent in the detailed description that follows. It should be understood, however, that the detailed description, while indicating embodiments of the present invention, is given by way of illustration only, not limitation. Various changes and modifications within the scope of the invention will become apparent to those skilled in the art from the detailed description.

BRIEF DESCRIPTION OF THE DRAWING

[0020] The following figures are for illustration purposes only and not for limitation.

[0021] **Figure 1** shows exemplary protein levels in in vitro transcription of FFL mRNA samples purified according to provided methods, including exposure to urea, along with various controls as shown by gel electrophoresis and Coomassie staining.

[0022] **Figure 2** shows exemplary firefly luciferase (FFL) mRNA levels in in vitro transcription samples purified according to provided methods as compared to mRNA purified according to traditional methods as shown by agarose gel electrophoresis and ethidium bromide staining.

[0023] **Figure 3** shows exemplary protein levels in *in vitro* transcription samples of FFL mRNA purified according to provided methods, including TFF with and without exposure to 5M urea, as compared to mRNA purified according to traditional methods gel electrophoresis and Coomassie staining.

[0024] **Figure 4** depicts exemplary fluorescence data gathered from translated purified FFL mRNA provided from provided methods as compared to purified mRNA provided from traditional methods.

[0025] **Figure 5** shows exemplary protein levels from *in vitro* transcription samples of Factor IX (FIX) mRNA purified according to provided methods, including exposure to proteinase K and/or 5M Urea, as compared to mRNA purified according to traditional methods gel electrophoresis and Coomassie staining.

[0026] **Figure 6** shows exemplary FIX mRNA levels in *in vitro* transcription samples purified according to provided methods as shown by agarose gel electrophoresis and ethidium bromide staining.

[0027] **Figure 7** shows exemplary protein levels in *in vitro* transcription samples of cystic fibrosis transmembrane conductance regulator (CFTR) mRNA purified according to provided methods, including exposure to 2M KCl, as compared to mRNA purified according to traditional methods gel electrophoresis and Coomassie staining.

[0028] **Figure 8** shows exemplary CFTR mRNA levels in in vitro transcription samples purified according to provided methods, including exposure to 2M KCl, as shown by agarose gel electrophoresis and ethidium bromide staining.

[0029] **Figure 9** shows exemplary CFTR mRNA levels in in vitro transcription samples purified according to provided methods, including exposure to 2M KCl, as compared to mRNA purified according to traditional methods as shown by agarose gel electrophoresis and ethidium bromide staining.

DEFINITIONS

[0030] In order for the present invention to be more readily understood, certain terms are first defined below. Additional definitions for the following terms and other terms are set forth throughout the specification.

[0031] *Animal*: As used herein, the term "animal" refers to any member of the animal kingdom. In some embodiments, "animal" refers to humans, at any stage of development. In some embodiments, "animal" refers to non-human animals, at any stage of development. In certain embodiments, the non-human animal is a mammal (*e.g.*, a rodent, a mouse, a rat, a rabbit,

a monkey, a dog, a cat, a sheep, cattle, a primate, and/or a pig). In some embodiments, animals include, but are not limited to, mammals, birds, reptiles, amphibians, fish, insects, and/or worms. In some embodiments, an animal may be a transgenic animal, genetically-engineered animal, and/or a clone.

[0032] *Approximately or about*: As used herein, the term "approximately" or "about," as applied to one or more values of interest, refers to a value that is similar to a stated reference value. In certain embodiments, the term "approximately" or "about" refers to a range of values that fall within 25%, 20%, 19%, 18%, 17%, 16%, 15%, 14%, 13%, 12%, 11%, 10%, 9%, 8%, 7%, 6%, 5%, 4%, 3%, 2%, 1%, or less in either direction (greater than or less than) of the stated reference value unless otherwise stated or otherwise evident from the context (except where such number would exceed 100% of a possible value).

[0033] *Biologically active*: As used herein, the phrase "biologically active" refers to a characteristic of any agent that has activity in a biological system, and particularly in an organism. For instance, an agent that, when administered to an organism, has a biological effect on that organism, is considered to be biologically active.

[0034] *Expression*: As used herein, "expression" of a nucleic acid sequence refers to translation of an mRNA into a polypeptide (e.g., heavy chain or light chain of antibody), assemble multiple polypeptides (e.g., heavy chain or light chain of antibody) into an intact protein (e.g., antibody) and/or post-translational modification of a polypeptide or fully assembled protein (e.g., antibody). In this application, the terms "expression" and "production," and grammatical equivalent, are used inter-changeably.

[0035] *Functional*: As used herein, a "functional" biological molecule is a biological molecule in a form in which it exhibits a property and/or activity by which it is characterized.

[0036] *Improve, increase, or reduce*: As used herein, the terms "improve," "increase" or "reduce," or grammatical equivalents, indicate values that are relative to a baseline measurement, such as a measurement in the same individual prior to initiation of the treatment described herein, or a measurement in a control subject (or multiple control subject) in the absence of the

treatment described herein. A "control subject" is a subject afflicted with the same form of disease as the subject being treated, who is about the same age as the subject being treated.

[0037] *Impurities*: As used herein, the term "impurities" refers to substances inside a confined amount of liquid, gas, or solid, which differ from the chemical composition of the target material or compound. Impurities are also referred to as contaminants.

[0038] *In Vitro*: As used herein, the term "*in vitro*" refers to events that occur in an artificial environment, *e.g.*, in a test tube or reaction vessel, in cell culture, *etc.*, rather than within a multi-cellular organism.

[0039] *In Vivo*: As used herein, the term "*in vivo*" refers to events that occur within a multi-cellular organism, such as a human and a non-human animal. In the context of cell-based systems, the term may be used to refer to events that occur within a living cell (as opposed to, for example, *in vitro* systems).

[0040] *Isolated*: As used herein, the term "isolated" refers to a substance and/or entity that has been (1) separated from at least some of the components with which it was associated when initially produced (whether in nature and/or in an experimental setting), and/or (2) produced, prepared, and/or manufactured by the hand of man. Isolated substances and/or entities may be separated from about 10%, about 20%, about 30%, about 40%, about 50%, about 60%, about 70%, about 80%, about 90%, about 91%, about 92%, about 93%, about 94%, about 95%, about 96%, about 97%, about 98%, about 99%, or more than about 99% of the other components with which they were initially associated. In some embodiments, isolated agents are about 80%, about 85%, about 90%, about 91%, about 92%, about 93%, about 94%, about 95%, about 96%, about 97%, about 98%, about 99%, or more than about 99% pure. As used herein, a substance is "pure" if it is substantially free of other components. As used herein, calculation of percent purity of isolated substances and/or entities should not include excipients (*e.g.*, buffer, solvent, water, *etc.*).

[0041] *messenger RNA (mRNA):* As used herein, the term "messenger RNA (mRNA)" refers to a polynucleotide that encodes at least one polypeptide. mRNA as used herein

encompasses both modified and unmodified RNA. mRNA may contain one or more coding and non-coding regions.

[0042] *mRNA integrity*: As used herein, the term "mRNA integrity" generally refers to the quality of mRNA. In some embodiments, mRNA integrity refers to the percentage of mRNA that is not degraded after a purification process (e.g., tangential flow filtration). mRNA integrity may be determined using methods well known in the art, for example, by RNA agarose gel electrophoresis (e.g., Ausubel et al., John Weley & Sons, Inc., 1997, Current Protocols in Molecular Biology).

[0043] *Nucleic acid*: As used herein, the term "nucleic acid," in its broadest sense, refers to any compound and/or substance that is or can be incorporated into a polynucleotide chain. In some embodiments, a nucleic acid is a compound and/or substance that is or can be incorporated into a polynucleotide chain via a phosphodiester linkage. In some embodiments, "nucleic acid" refers to individual nucleic acid residues (*e.g.*, nucleotides and/or nucleosides). In some embodiments, "nucleic acid" refers to a polynucleotide chain comprising individual nucleic acid residues. In some embodiments, "nucleic acid" encompasses RNA as well as single and/or double-stranded DNA and/or cDNA. Furthermore, the terms "nucleic acid," "DNA," "RNA," and/or similar terms include nucleic acid analogs, *i.e.*, analogs having other than a phosphodiester backbone. For example, the so-called "peptide nucleic acids," which are known in the art and have peptide bonds instead of phosphodiester bonds in the backbone, are considered within the scope of the present invention. The term "nucleotide sequence encoding an amino acid sequence" includes all nucleotide sequences that are degenerate versions of each other and/or encode the same amino acid sequence. Nucleotide sequences that encode proteins and/or RNA may include introns. Nucleic acids can be purified from natural sources, produced using recombinant expression systems and optionally purified, chemically synthesized, *etc.* Where appropriate, *e.g.*, in the case of chemically synthesized molecules, nucleic acids can comprise nucleoside analogs such as analogs having chemically modified bases or sugars, backbone modifications, *etc.* A nucleic acid sequence is presented in the 5' to 3' direction unless otherwise indicated. In some embodiments, a nucleic acid is or comprises natural nucleosides (*e.g.*, adenosine, thymidine, guanosine, cytidine, uridine, deoxyadenosine, deoxythymidine,

deoxyguanosine, and deoxycytidine); nucleoside analogs (*e.g.*, 2-aminoadenosine, 2-thiothymidine, inosine, pyrrolo-pyrimidine, 3-methyl adenosine, 5-methylcytidine, C-5 propynyl-cytidine, C-5 propynyl-uridine, 2-aminoadenosine, C5-bromouridine, C5-fluorouridine, C5-iodouridine, C5-propynyl-uridine, C5-propynyl-cytidine, C5-methylcytidine, 2-aminoadenosine, 7-deazaadenosine, 7-deazaguanosine, 8-oxoadenosine, 8-oxoguanosine, O(6)-methylguanine, and 2-thiocytidine); chemically modified bases; biologically modified bases (*e.g.*, methylated bases); intercalated bases; modified sugars (*e.g.*, 2'-fluororibose, ribose, 2'-deoxyribose, arabinose, and hexose); and/or modified phosphate groups (*e.g.*, phosphorothioates and 5'-*N*-phosphoramidite linkages). In some embodiments, the present invention is specifically directed to "unmodified nucleic acids," meaning nucleic acids (*e.g.*, polynucleotides and residues, including nucleotides and/or nucleosides) that have not been chemically modified in order to facilitate or achieve delivery.

[0044] *Patient:* As used herein, the term "patient" or "subject" refers to any organism to which a provided composition may be administered, *e.g.*, for experimental, diagnostic, prophylactic, cosmetic, and/or therapeutic purposes. Typical patients include animals (*e.g.*, mammals such as mice, rats, rabbits, non-human primates, and/or humans). In some embodiments, a patient is a human. A human includes pre and post natal forms.

[0045] *Pharmaceutically acceptable*: The term "pharmaceutically acceptable" as used herein, refers to substances that, within the scope of sound medical judgment, are suitable for use in contact with the tissues of human beings and animals without excessive toxicity, irritation, allergic response, or other problem or complication, commensurate with a reasonable benefit/risk ratio.

[0046] *Prematurely aborted RNA sequences*: The term "prematurely aborted RNA sequences", as used herein, refers to incomplete products of an mRNA synthesis reaction (e.g., an *in vitro* synthesis reaction). For a variety of reasons, RNA polymerases do not always complete transcription of a DNA template; i.e., RNA synthesis terminates prematurely. Possible causes of premature termination of RNA synthesis include quality of the DNA template, polymerase terminator sequences for a particular polymerase present in the template, degraded buffers, temperature, depletion of ribonucleotides, and mRNA secondary structures. Prematurely

aborted RNA sequences may be any length that is less than the intended length of the desired transcriptional product. For example, prematurely aborted mRNA sequences may be less than 1000 bases, less than 500 bases, less than 100 bases, less than 50 bases, less than 40 bases, less than 30 bases, less than 20 bases, less than 15 bases, less than 10 bases or fewer.

[0047] *Salt*: As used herein the term "salt" refers to an ionic compound that does or may result from a neutralization reaction between an acid and a base.

[0048] *Subject*: As used herein, the term "subject" refers to a human or any non-human animal (e.g., mouse, rat, rabbit, dog, cat, cattle, swine, sheep, horse or primate). A human includes pre- and post-natal forms. In many embodiments, a subject is a human being. A subject can be a patient, which refers to a human presenting to a medical provider for diagnosis or treatment of a disease. The term "subject" is used herein interchangeably with "individual" or "patient." A subject can be afflicted with or is susceptible to a disease or disorder but may or may not display symptoms of the disease or disorder.

[0049] *Substantially*: As used herein, the term "substantially" refers to the qualitative condition of exhibiting total or near-total extent or degree of a characteristic or property of interest. One of ordinary skill in the biological arts will understand that biological and chemical phenomena rarely, if ever, go to completion and/or proceed to completeness or achieve or avoid an absolute result. The term "substantially" is therefore used herein to capture the potential lack of completeness inherent in many biological and chemical phenomena.

[0050] *Substantially free*: As used herein, the term "substantially free" refers to a state in which relatively little or no amount of a substance to be removed (e.g., prematurely aborted RNA sequences) are present. For example, "substantially free of prematurely aborted RNA sequences" means the prematurely aborted RNA sequences are present at a level less than approximately 5%, 4%, 3%, 2%, 1.0%, 0.9%, 0.8%, 0.7%, 0.6%, 0.5%, 0.4%, 0.3%, 0.2%, 0.1% or less (w/w) of the impurity. Alternatively, "substantially free of prematurely aborted RNA sequences" means the prematurely aborted RNA sequences are present at a level less than about 100 ng, 90 ng, 80 ng, 70 ng, 60 ng, 50 ng, 40 ng, 30 ng, 20 ng, 10 ηg, 1 ηg, 500 ρg, 100 ρg, 50 ρg, 10 ρg, or less.

DETAILED DESCRIPTION

[0051] The present invention provides, among other things, improved methods for purifying mRNA from an impure preparation (e.g., *in vitro* synthesis reaction mixture) based on tangential flow filtration. In some embodiments, an inventive method according to the present invention includes steps of (a) subjecting an impure preparation comprising *in vitro* synthesized mRNA to a denaturing condition, and (b) purifying the mRNA from the impure preparation from step (a) by tangential flow filtration, wherein the mRNA purified from step (b) is substantially free of prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis.

[0052] Various aspects of the invention are described in detail in the following sections. The use of sections is not meant to limit the invention. Each section can apply to any aspect of the invention. In this application, the use of "or" means "and/or" unless stated otherwise.

Synthesis of mRNA

[0053] mRNA is typically thought of as the type of RNA that carries information from DNA to the ribosome. The existence of mRNA is typically very brief and includes processing and translation, followed by degradation. Typically, in eukaryotic organisms, mRNA processing comprises the addition of a "cap" on the N-terminal (5') end, and a "tail" on the C-terminal (3') end. A typical cap is a 7-methylguanosine cap, which is a guanosine that is linked through a 5'-5'-triphosphate bond to the first transcribed nucleotide. The presence of the cap is important in providing resistance to nucleases found in most eukaryotic cells. The tail is typically a polyadenylation event whereby a polyadenylyl moiety is added to the 3' end of the mRNA molecule. The presence of this "tail" serves to protect the mRNA from exonuclease degradation. Messenger RNA is translated by the ribosomes into a series of amino acids that make up a protein.

[0054] mRNAs according to the present invention may be synthesized according to any of a variety of known methods. For example, mRNAs according to the present invention may be synthesized via *in vitro* transcription (IVT). Briefly, IVT is typically performed with a linear or circular DNA template containing a promoter, a pool of ribonucleotide triphosphates, a buffer

system that may include DTT and magnesium ions, and an appropriate RNA polymerase (e.g., T3, T7 or SP6 RNA polymerase), DNAse I, pyrophosphatase, and/or RNAse inhibitor. The exact conditions will vary according to the specific application. The presence of these reagents is undesirable in the final product according to several embodiments and may thus be referred to as impurities and a preparation containing one or more of these impurities may be referred to as an impure preparation.

[0055] mRNAs according to the present invention may be purified on a commercial scale. In some embodiments, the mRNA is purified at a scale of or greater than 0.1 grams, 0.5 grams, 1 gram, 2 grams, 3 grams, 4 grams, 5 grams, 6 grams, 7 grams, 8 grams, 9 grams, 10 gram, 20 grams, 30 grams, 40 grams, 50 grams, 60 grams, 70 grams, 80 grams, 90 grams, 100 grams, 200 grams, 300 grams, 400 grams, 500 grams, 600 grams, 700 grams, 800 grams, 900 grams, or 1,000 grams per batch.

[0056] According to various embodiments, the present invention may be used to purify *in vitro* synthesized mRNA of a variety of lengths. In some embodiments, the present invention may be used to purify *in vitro* synthesized mRNA of greater than about 1 kb, 1.5 kb, 2 kb, 2.5 kb, 3 kb, 3.5 kb, 4 kb, 4.5 kb, 5 kb, 6 kb, 7 kb, 8 kb, 9 kb, 10 kb, 11 kb, 12 kb, 13 kb, 14 kb, or 15 kb in length. In some embodiments, the present invention may be used to purify mRNA containing one or more modifications that typically enhance stability. In some embodiments, one or more modifications are selected from modified nucleotide, modified sugar phosphate backbones, 5' and/or 3' untranslated region. In some embodiments, the present invention may be used to purify *in vitro* synthesized mRNA that is unmodified.

[0057] Typically, mRNAs are modified to enhance stability. Modifications of mRNA can include, for example, modifications of the nucleotides of the RNA. An modified mRNA according to the invention can thus include, for example, backbone modifications, sugar modifications or base modifications. In some embodiments, antibody encoding mRNAs (e.g., heavy chain and light chain encoding mRNAs) may be synthesized from naturally occurring nucleotides and/or nucleotide analogues (modified nucleotides) including, but not limited to, purines (adenine (A), guanine (G)) or pyrimidines (thymine (T), cytosine (C), uracil (U)), and as modified nucleotides analogues or derivatives of purines and pyrimidines, such as e.g. 1-methyl-

adenine, 2-methyl-adenine, 2-methylthio-N-6-isopentenyl-adenine, N6-methyl-adenine, N6-isopentenyl-adenine, 2-thio-cytosine, 3-methyl-cytosine, 4-acetyl-cytosine, 5-methyl-cytosine, 2,6-diaminopurine, 1-methyl-guanine, 2-methyl-guanine, 2,2-dimethyl-guanine, 7-methyl-guanine, inosine, 1-methyl-inosine, pseudouracil (5-uracil), dihydro-uracil, 2-thio-uracil, 4-thio-uracil, 5-carboxymethylaminomethyl-2-thio-uracil, 5-(carboxyhydroxymethyl)-uracil, 5-fluoro-uracil, 5-bromo-uracil, 5-carboxymethylaminomethyl-uracil, 5-methyl-2-thio-uracil, 5-methyl-uracil, N-uracil-5-oxyacetic acid methyl ester, 5-methylaminomethyl-uracil, 5-methoxyaminomethyl-2-thio-uracil, 5'-methoxycarbonylmethyl-uracil, 5-methoxy-uracil, uracil-5-oxyacetic acid methyl ester, uracil-5-oxyacetic acid (v), 1-methyl-pseudouracil, queosine, .beta.-D-mannosyl-queosine, wybutoxosine, and phosphoramidates, phosphorothioates, peptide nucleotides, methylphosphonates, 7-deazaguanosine, 5-methylcytosine and inosine. The preparation of such analogues is known to a person skilled in the art e.g. from the U.S. Pat. No. 4,373,071, U.S. Pat. No. 4,401,796, U.S. Pat. No. 4,415,732, U.S. Pat. No. 4,458,066, U.S. Pat. No. 4,500,707, U.S. Pat. No. 4,668,777, U.S. Pat. No. 4,973,679, U.S. Pat. No. 5,047,524, U.S. Pat. No. 5,132,418, U.S. Pat. No. 5,153,319, U.S. Pat. Nos. 5,262,530 and 5,700,642, the disclosure of which is included here in its full scope by reference.

[0058] Typically, mRNA synthesis includes the addition of a "cap" on the N-terminal (5') end, and a "tail" on the C-terminal (3') end. The presence of the cap is important in providing resistance to nucleases found in most eukaryotic cells. The presence of a "tail" serves to protect the mRNA from exonuclease degradation.

[0059] Thus, in some embodiments, mRNAs include a 5' cap structure. A 5' cap is typically added as follows: first, an RNA terminal phosphatase removes one of the terminal phosphate groups from the 5' nucleotide, leaving two terminal phosphates; guanosine triphosphate (GTP) is then added to the terminal phosphates via a guanylyl transferase, producing a 5'5'5 triphosphate linkage; and the 7-nitrogen of guanine is then methylated by a methyltransferase. Examples of cap structures include, but are not limited to, m7G(5')ppp (5'(A,G(5')ppp(5')A and G(5')ppp(5')G.

[0060] While mRNA provided from *in vitro* transcription reactions may be desirable in some embodiments, other sources of mRNA are contemplated as within the scope of the invention including wild-type mRNA produced from bacteria, fungi, plants, and/or animals.

[0061] In some embodiments, mRNAs include a 5' and/or 3' untranslated region. In some embodiments, a 5' untranslated region includes one or more elements that affect an mRNA's stability or translation, for example, an iron responsive element. In some embodiments, a 5' untranslated region may be between about 50 and 500 nucleotides in length.

[0062] In some embodiments, a 3' untranslated region includes one or more of a polyadenylation signal, a binding site for proteins that affect an mRNA's stability of location in a cell, or one or more binding sites for miRNAs. In some embodiments, a 3' untranslated region may be between 50 and 500 nucleotides in length or longer.

[0063] The present invention may be used to purify mRNAs encoding a variety of proteins. Non-limiting examples of purification of mRNAs encoding firefly luciferase, Factor IX, and CFTR, are described in detail in the Examples section.

Denaturing Conditions and Denaturation Agents

[0064] Typically, changing the conformation of a protein or nucleic acid either temporarily or permanently by disrupting intermolecular forces is called denaturation. Denaturation results in structural change and often to a loss of activity. Since the native conformation of a molecule is usually the most water soluble, disrupting the secondary and tertiary structures of a molecule may cause changes in solubility and may result in precipitation of the protein or nucleic acid from solution. Surprisingly, as described herein, using a denaturing condition in combination with tangential flow filtration (TFF) can facilitate mRNA purification while still maintaining the integrity of mRNA.

[0065] As used herein, the term "denaturing condition" refers to any chemical or physical conditions that can cause denaturation. Exemplary denaturing conditions include, but are not limited to, chemical reagents, high temperatures, extreme pH, etc.

[0066] In some embodiments, a denaturing condition is achieved through adding one or more denaturing agents to an impure preparation containing mRNA to be purified. In some embodiments, a denaturing agent suitable for the present invention is a protein and/or DNA denaturing agent. In some embodiments, a denaturing agent may be: 1) an enzyme (such as a serine proteinase or a DNase), 2) an acid, 3) a solvent, 4) a cross-linking agent, 5) a chaotropic agent, 6) a reducing agent, and/or 7) high ionic strength via high salt concentrations. In some embodiments, a particular agent may fall into more than one of these categories.

[0067] In some embodiments, one or more enzymes may be used as denaturing agents to degrade proteins and DNA templates used in mRNA synthesis. In some embodiments, suitable enzymes include, but are not limited to, serine proteases such as chymotrypsin and chymotrypsin-like serine proteases, trypsin and trypsin-like serine proteases, elastase and elastase-like serine proteases, subtilisin and subtilisin-like serine proteases, and combinations thereof, deoxyribonucleases (DNases) such as deoxyribonuclease I, II and/or IV, restriction enzymes such as EcoRI, EcoRII, BamHI, HindIII, SpeI, SphI, StuI, XbaI, and combination thereof.

[0068] In some embodiments, an acid may be used as a denaturing agent. In some embodiments, a suitable acid may be acetic acid, formic acid, oxalic acid, citric acid, benzoic acid, chloroacetic acid, dichloroacetic acid, trichloroacetic acid, ascorbic acid, sulfosalicylic acid, and combinations thereof.

[0069] In some embodiments, a solvent may be used as a denaturing agent. In some embodiments, a solvent may be isopropyl alcohol, acetone, methyl ethyl ketone, methyl isobutyl ketone, ethanol, methanol, denatonium, and combinations thereof.

[0070] In some embodiments, a chaotropic agent may be sued as a denaturing agent. Choatropic agents are substances which disrupt the structure of macromolecules such as proteins and nucleic acids by interfering with non-covalent forces such as hydrogen bonds and van der Waals forces. In some embodiments, a chaotropic agent may be urea, thiourea, guanidinium chloride, guanidinium thiocyanate, guanidinium isothiocyanate, lithium acetate, magnesium chloride, sodium dodecyl sulfate, lithium perchlorate and combination thereof.

[0071] In some embodiments, an impure preparation containing mRNA to be purified is treated with urea. In some embodiments, an amount of urea is added such that the resulting urea concentration is about 1M or greater. In some embodiments, urea is added such that the resulting urea concentration is about 2 M or greater, 3 M or greater, 4 M or greater, 5 M or greater, 6 M or greater, 7 M or greater, 8 M or greater, 9 M or greater, or 10 M or greater. In some embodiments, an impure preparation containing mRNA to be purified is treated with guanidinium thiocyanate. In some embodiments, an amount of guanidinium thiocyanate is added such that the resulting guanidinium thiocyanate concentration is about 1M or greater. In some embodiments, guanidinium thiocyanate is added such that the resulting guanidinium thiocyanate concentration is about 2 M or greater, 3 M or greater, 4 M or greater, 5 M or greater, 6 M or greater, 7 M or greater, 8 M or greater, 9 M or greater, or 10 M or greater.

[0072] In some embodiments, a reducing agent may be used as a denaturing agent. Reducing agents are compounds that donate an electron to another species, thus becoming oxidized itself. In some embodiments, a reducing agent may be lithium aluminum hydride, sodium amalgam, diborane, sodium borohydride, sulfites, diisobutylaluminum hydride, phosphites, carbon monoxide, 2-mercaptoethanol, dithiothreitol, or tris(2-carboxyethyl)phosphine, and combinations thereof.

[0073] In some embodiments, one or more of pH, heat, and/or heavy metals (such as lead, mercury or cadmium) may also be used a denaturing agents. Extremes of pH are known to cause a protein to denature. Although the backbone of a protein chain is neutral, the amino acid residues that comprise the protein often contain acidic and basic groups. These groups are usually charged and can form salt bridges with a group of opposite charge. Accordingly, extremes of pH can change the charges on these acidic and basic groups, disrupting salt bridges.

[0074] In some embodiments, less drastic changes in pH may also affect the activity and solubility of a protein. Like individual amino acids, proteins have an isoelectric point at which the number of negative charges equals the number of positive charges. This is frequently the point of minimum water solubility. At the isoelectric pH, there is no net charge on the molecule. Individual molecules have a tendency to approach one another, coagulate, and precipitate out of solution. At a pH above or below the isoelectric pH, the molecules have a net negative or

positive charge, respectively. Thus when protein molecules approach each other, they have the same overall charge and repulse each other.

[0075] In some embodiments, heat may be used as a denaturing agent. Heat can supply kinetic energy to protein molecules, causing their atoms to vibrate more rapidly. In some embodiments, this will disrupt relatively weak forces such as hydrogen bonds and hydrophobic interactions. Heat is also used in sterilization to denature and hence destroy the enzymes in bacteria.

[0076] In some embodiments, salts of metal ions such as mercury(II), lead(II), and silver may be used as denaturing agents due to their ability to form strong bonds with disulfide groups and with the carboxylate ions of the acidic amino acids. Thus, they disrupt both disulfide bridges and salt linkages and cause the protein to precipitate out of solution as an insoluble metal-protein salt.

[0077] In some embodiments, high concentrations of salt (high salinity) may also be used as a denaturing agent. High concentrations of salts are known to cause both proteins and nucleic acids to precipitate from an aqueous solution. In some embodiments, a high concentration of salt may be between 1M and 10M, inclusive. In some embodiments, a high concentration of salt may be between 2M and 9M, inclusive. In some embodiments, a high concentration of salt may be between 2M and 8M, inclusive. In some embodiments, a high concentration of salt may be between 2M and 5M, inclusive. In some embodiments, a high concentration of salt may be greater than 1M concentration. In some embodiments, a high concentration of salt may be greater than 2M concentration. In some embodiments, a high concentration of salt may be greater than 3M concentration. In some embodiments, a high concentration of salt may be greater than 4M concentration. In some embodiments, a high concentration of salt may be greater than 5M concentration. In some embodiments, a high concentration of salt may be greater than 6M concentration. In some embodiments, a high concentration of salt may be greater than 7M concentration. In some embodiments, a high concentration of salt may be greater than 8M concentration. In some embodiments, a single salt is used as a denaturing agent. In some embodiments, more than one salt is used as a denaturing agent.

[0078] In some embodiments, a salt used as a denaturing agent may be a calcium salt, an iron salt, a magnesium salt, a potassium salt, a sodium salt, or a combination thereof. Exemplary specific salts suitable for use as denaturing agents in some embodiments include, but are not limited to, potassium chloride (KCl), sodium chloride (NaCl), lithium chloride (LiCl), calcium chloride ($CaCl_2$), potassium bromide (KBr), sodium bromide (NaBr), lithium bromide (LiBr). In some embodiments, the denaturing agent the impure preparation is subjected to is potassium chloride (KCl). In some embodiments, KCl is added such that the resulting KCl concentration is about 1M or greater. In some embodiments, KCl is added such that the resulting KCl concentration is about 2 M or greater, 3 M or greater, 4 M or greater, or 5 M or greater.

[0079] In some embodiments, it may be desirable to incubate the impure preparation with one or more denaturing agents for a period of time. In some embodiments, the impure preparation is incubated with a denaturing agent for less than one minute. In some embodiments, the impure preparation is incubated with a denaturing agent for one minute. In some embodiments, the impure preparation is incubated with a denaturing agent for two minutes. In some embodiments, the impure preparation is incubated with a denaturing agent for three minutes. In some embodiments, the impure preparation is incubated with a denaturing agent for four minutes. In some embodiments, the impure preparation is incubated with a denaturing agent for five minutes. In some embodiments, the impure preparation is incubated with a denaturing agent for ten minutes. In some embodiments, the impure preparation is incubated with a denaturing agent for one hour. In some embodiments, the impure preparation is incubated with a denaturing agent for two hours.

[0080] In some embodiments, the impure preparation is incubated with one or more denaturing agents at room temperature (e.g., about 20-25 $^{\circ}C$). In some embodiments, the impure preparation is incubated with one or more denaturing agents at a temperature below room temperature. In some embodiments, the impure preparation is incubated with one or more denaturing agents at a temperature above room temperature.

Purification

[0081] In several embodiments, before and/or after exposure to a denaturing condition, tangential flow filtration is used to purify the mRNA from an impure preparation. In some embodiments, tangential flow filtration is performed before a cap and poly-A tail are added to the *in vitro* synthesized mRNA. In some embodiments, tangential flow filtration is performed after a cap and poly-A tail are added to the *in vitro* synthesized mRNA. In some embodiments, tangential flow filtration is performed both before and after a cap and poly-A tail are added to the *in vitro* synthesized mRNA.

Traditional Membrane Filtration

[0082] Generally, membrane filtration involves separating solids from fluids using one or more interposed permeable membranes. Membrane filtration may also be used to filter particles from a gaseous sample. There are two major forms of membrane filtration, passive filtration which proceeds solely due to solution-diffusion, and active filtration which uses positive pressure or negative pressure (i.e. vacuum) to force the liquid or gas across the membrane.

[0083] Traditional membrane filtration is also known as "dead-end" filtration. In this format, the feed is loaded onto a membrane and forced through by positive or negative pressure. Dead-end filtration tends to be inexpensive and simple, with the major drawbacks being fouling or clogging of the membrane with non- or slowly-permeating solute (also referred to as the retentate), and concentration polarization. Generally, membranes tend to clog or foul more rapidly as driving forces increase. As a membrane fouls or clogs, the rate of filtration is reduced and eventually no permeate is able to pass through until the filter is changed or cleaned. Concentration polarization is a phenomenon wherein non-permeable solute collects on the surface of a filter and eventually forms a type of secondary membrane, which further impedes travel of permeable solute across the membrane. As a result, dead-end filtration is typically used in batch type processes.

Tangential Flow Filtration

[0084] Tangential flow filtration (TFF), also referred to as cross-flow filtration, is a type of filtration wherein the material to be filtered is passed tangentially *across* a filter rather than

through it. In TFF, undesired permeate passes through the filter, while the desired retentate passes along the filter and is collected downstream. It is important to note that the desired material is typically contained in the retentate in TFF, which is the opposite of what one normally encounters in traditional-dead end filtration.

[0085] Depending upon the material to be filtered, TFF is usually used for either microfiltration or ultrafiltration. Microfiltration is typically defined as instances where the filter has a pore size of between 0.05 μm and 1.0 μm, inclusive, while ultrafiltration typically involves filters with a pore size of less than 0.05 μm. Pore size also determines the nominal molecular weight limits (NMWL), also referred to as the molecular weight cut off (MWCO) for a particular filter, with microfiltration membranes typically having NMWLs of greater than 1,000 kilodaltons (kDa) and ultrafiltration filters having NMWLs of between 1 kDa and 1,000 kDa.

[0086] A principal advantage of tangential flow filtration is that non-permeable particles that may aggregate in and block the filter (sometimes referred to as "filter cake") during traditional "dead-end" filtration, are instead carried along the surface of the filter. This advantage allows tangential flow filtration to be widely used in industrial processes requiring continuous operation since down time is significantly reduced because filters do not generally need to be removed and cleaned.

[0087] Tangential flow filtration can be used for several purposes including concentration and diafiltration, among others. Concentration is a process whereby solvent is removed from a solution while solute molecules are retained. In order to effectively concentrate a sample, a membrane having a NMWL or MWCO that is substantially lower than the molecular weight of the solute molecules to be retained is used. Generally, one of skill may select a filter having a NMWL or MWCO of three to six times below the molecular weight of the target molecule(s).

[0088] Diafiltration is a fractionation process whereby small undesired particles are passed through a filter while larger desired molecules are maintained in the retentate without changing the concentration of those molecules in solution. Diafiltration is often used to remove salts or reaction buffers from a solution. Diafiltration may be either continuous or discontinuous.

In continuous diafiltration, a diafiltration solution is added to the sample feed at the same rate that filtrate is generated. In discontinuous diafiltration, the solution is first diluted and then concentrated back to the starting concentration. Discontinuous diafiltration may be repeated until a desired concentration of the solute molecules is reached.

[0089] At least three process variables that are important in a typical TFF process: the transmembrane pressure, feed rate, and flow rate of the permeate. The transmembrane pressure is the force that drives fluid through the filter, carrying with it permeable molecules. In some embodiments, the transmembrane pressure is between 1 and 30 pounds per square inch (psi), inclusive.

[0090] The feed rate (also known as the crossflow velocity) is the rate of the solution flow through the feed channel and across the filter. The feed rate determines the force that sweeps away molecules that may otherwise clog or foul the filter and thereby restrict filtrate flow. In some embodiments, the feed rate is between 50 and 500 mL/minute. In some embodiments, the feed rate is between 50 and 400 mL/minute. In some embodiments, the feed rate is between 50 and 300 mL/minute. In some embodiments, the feed rate is between 50 and 200 mL/minute. In some embodiments, the feed rate is between 75 and 200 mL/minute. In some embodiments, the feed rate is between 100 and 200 mL/minute. In some embodiments, the feed rate is between 125 and 175 mL/minute. In some embodiments, the feed rate is 130 mL/minute. In some embodiments, the feed rate is between 60 mL/min and 220 mL/min. In some embodiments, the feed rate is 60 mL/min or greater. In some embodiments, the feed rate is 100 mL/min or greater. In some embodiments, the feed rate is 150 mL/min or greater. In some embodiments, the feed rate is 200 mL/min or greater. In some embodiments, the feed rate is 220 mL/min or greater.

[0091] The flow rate of the permeate is the rate at which the permeate is removed from the system. For a constant feed rate, increasing permeate flow rates can increase the pressure across the filter, leading to enhanced filtration rates while also potentially increasing the risk of filter clogging or fouling. The principles, theory, and devices used for TFF are described in Michaels et al., "Tangential Flow Filtration" in Separations Technology, Pharmaceutical and Biotechnology Applications (W. P. Olson, ed., Interpharm Press, Inc., Buffalo Grove, Ill. 1995).

See also U.S. Pat. Nos. 5,256,294 and 5,490,937 for a description of high-performance tangential flow filtration (HP-TFF), which represents an improvement to TFF. In some embodiments, the flow rate is between 10 and 100 mL/minute. In some embodiments, the flow rate is between 10 and 90 mL/minute. In some embodiments, the flow rate is between 10 and 80 mL/minute. In some embodiments, the flow rate is between 10 and 70 mL/minute. In some embodiments, the flow rate is between 10 and 60 mL/minute. In some embodiments, the flow rate is between 10 and 50 mL/minute. In some embodiments, the flow rate is between 10 and 40 mL/minute. In some embodiments, the flow rate is between 20 and 40 mL/minute. In some embodiments, the flow rate is 30 mL/minute.

[0092] Any combinations of various process variables described herein may be used. In some embodiments, the tangential flow filtration is performed at a feed rate of approximately 100-200 mL/minute (e.g., approximately 100-180 mL/minute, 100-160 mL/minute, 100-140 mL/minute, 110-190 mL/minute, 110-170 mL/minute, or 110-150 mL/minute) and/or a flow rate of approximately 10-50 mL/minute (e.g., approximately 10-40 mL/minute, 10-30 mL/minute, 20-50 mL/minute, or 20-40 mL/minute). In some embodiments, the tangential flow filtration is performed at a feed rate of approximately 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, or 200 mL/minute and/or a flow rate of approximately 10, 20, 30, 40, or 50 mL/minute.

[0093] Further flow rates to accommodate large (commercial) scale purification would entail the tangential flow filtration being performed at a feed rate of approximately 10 L-200 L/minute. (e.g., approximately 10-180 L/minute, 100-160 L/minute, 100-140 L/minute, 110-190 L/minute, 110-170 L/minute, or 110-150 L/minute) and/or a flow rate of approximately 10-50 L/minute (e.g., approximately 10-40 L/minute, 10-30 L/minute, 20-50 L/minute, or 20-40 L/minute). In some embodiments, the tangential flow filtration is performed at a feed rate of approximately 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, or 200 L/minute and/or a flow rate of approximately 10, 20, 30, 40, or 50 L/minute.

[0094] As described above, filters used in TFF may have any of a variety of pore sizes, and thus NMWLs. In some embodiments, a filter will have a NMWL of between 100kDa and 1,000 kDa. In some embodiments, a filter will have a NMWL of between 200 kDa and 700 kDa. In some embodiments, a filter will have a NMWL between 200 kDa and 500kDa. In some

embodiments, a filter has a NMWL of 300 kDa. In some embodiments, a filter has a NMWL of 500 kDa.

[0095] In some embodiments, a tangential flow filtration according to the invention is performed using only aqueous solvents. In some embodiments, a tangential flow filtration according to the invention is performed using water as the solvent.

Characterization of purified mRNA

[0096] In various embodiments, mRNA purified according to the present invention is substantially free of impurities from mRNA synthesis process including, but not limited to, prematurely aborted RNA sequences, DNA templates, and/or enzyme reagents used in *in vitro* synthesis.

[0097] A particular advantage provided by the present invention is the ability to remove or eliminate a high degree of prematurely aborted RNA sequences (also known as "shortmers"). In some embodiments, a method according to the invention removes more than about 90%, 95%, 96%, 97%, 98%, 99% or substantially all prematurely aborted RNA sequences . In some embodiments, mRNA purified according to the present invention is substantially free of prematurely aborted RNA sequences. In some embodiments, mRNA purified according to the present invention contains less than about 5% (e.g., less than about 4%, 3%, 2%, or 1%) of prematurely aborted RNA sequences. In some embodiments, mRNA purified according to the present invention contains less than about 1% (e.g., less than about 0.9%, 0.8%, 0.7%, 0.6%, 0.5%, 0.4%, 0.3%, 0.2%, or 0.1%) of prematurely aborted RNA sequences. In some embodiments, mRNA purified according to the present invention contains contains undetectable prematurely aborted RNA sequences as determined by, e.g., eithidium bromide and/or Coomassie staining. In some embodiments, prematurely aborted RNA sequences comprise less than 15 bases (e.g., less than 14, 13, 12, 11, 10, 9 or 8 bases). In some embodiments, the prematurely aborted RNA sequences comprise about 8-12 bases.

[0098] In some embodiments, a method according to the present invention removes or eliminates a high degree of enzyme reagents used in *in vitro* synthesis including, but not limited

to, T7 RNA polymerase, DNAse I, pyrophosphatase, and/or RNAse inhibitor. In some embodiments, the present invention is particularly effective to remove T7 RNA polymerase. In some embodiments, a method according to the invention removes more than about 90%, 95%, 96%, 97%, 98%, 99% or substantially all enzyme reagents used in *in vitro* synthesis including. In some embodiments, mRNA purified according to the present invention is substantially free of enzyme reagents used in *in vitro* synthesis including. In some embodiments, mRNA purified according to the present invention contains less than about 5% (e.g., less than about 4%, 3%, 2%, or 1%) of enzyme reagents used in *in vitro* synthesis including. In some embodiments, mRNA purified according to the present invention contains less than about 1% (e.g., less than about 0.9%, 0.8%, 0.7%, 0.6%, 0.5%, 0.4%, 0.3%, 0.2%, or 0.1%) of enzyme reagents used in *in vitro* synthesis including. In some embodiments, mRNA purified according to the present invention contains undetectable enzyme reagents used in *in vitro* synthesis including as determined by, e.g., ethidium bromide and/or Coomassie staining.

[0099] In various embodiments, mRNA purified using a method described herein maintain high degree of integrity. As used herein, the term "mRNA integrity" generally refers to the quality of mRNA after purification. In some embodiments, mRNA integrity refers to the percentage of mRNA that is not degraded after tangential flow filtration. mRNA integrity may be determined using methods well known in the art, for example, by RNA agarose gel electrophoresis (e.g., Ausubel et al., John Weley & Sons, Inc., 1997, Current Protocols in Molecular Biology). In some embodiments, mRNA purified according to the present invention has an integrity greater than about 95% (e.g., greater than about 96%, 97%, 98%, 99% or more). In some embodiments, mRNA purified according to the present invention has an integrity greater than 98%. In some embodiments, mRNA purified according to the present invention has an integrity greater than 99%. In some embodiments, mRNA purified according to the present invention has an integrity of approximately 100%.

EXAMPLES

Example 1. Generation and Purification of Messenger RNA (mRNA)

Synthesis of mRNA

[0100] In each of the examples below, the synthesis of mRNA was conducted under complete RNAse-free conditions. All tubes, vials, pipette tips, pipettes, buffers, etc. were required to be nuclease-free, unless explicitly stated otherwise.

[0101] In the following examples, unless otherwise described, mRNA was synthesized via *in-vitro* transcription from a linearized DNA template. To produce the desired mRNA pre-cursor (IVT) construct, a mixture of ~100 ug of linearized DNA, rNTPs (3.33 mM), DTT (10 mM), T7 RNA polymerase, RNAse Inhibitor, Pyrophosphatase and reaction buffer (10x, 800mM Hepes (pH8.0), 20mM Spermidine, 250mM $MgCl_2$, pH 7.7) was prepared with RNase-free water to a final volume of 2.24 mL. The reaction mixture is incubated at 37°C for a range of time between 20 minutes- 120 minutes. Upon completion, the mixture is treated with DNase I for an additional 15 minutes and quenched accordingly.

Addition of 5' Cap and 3' Tail

[0102] The purified mRNA product from the aforementioned IVT step (and possibly initial TFF filtration as well) was denatured at 65°C for 10 minutes. Separately, portions of GTP (20 mM), S-adenosyl methionine, RNAse inhibitor, 2'-O-Methyltransferase and guanylyl transferase are mixed together with reaction buffer (10x, 500mM Tris-HCl (pH8.0), 60mM KCl, 12.5mM $MgCl_2$) to a final concentration of 8.3 mL. Upon denaturation, the mRNA is cooled on ice and then added to the reaction mixture. The combined solution is incubated for a range of time at 37°C for 20-90 minutes. Upon completion, aliquots of ATP (20 mM), PolyA Polymerase and tailing reaction buffer (10x, 500mM Tris-HCl (pH8.0), 2.5M NaCl, 100mM $MgCl_2$) are added and the total reaction mixture is further incubated at 37°C for a range of time from 20-45 minutes. Upon completion, the final reaction mixture is quenched and purified accordingly.

Purification via Tangential Flow Filtration

[0103] In the following examples, unless otherwise described, the tangential flow filtration (TFF) system consisted of a filtration membrane and a peristaltic pump (Millipore Labscale TFF system) with tangential circulation of the fluid across the membrane at a feed rate of ~130 mL/min with a 30 mL/min flow rate for the permeate. The TFF membrane employed was a MidiKros 500kDa mPES 115cm^2 (Spectrum Labs). Before use, the filter cartridge was washed with nuclease free water and further cleaned with 0.2N NaOH. Finally the system was cleaned with nuclease free water until the pH of permeate and retentate reached a pH ~6.

Example 2. Analysis of Purified mRNA

Testing for Presence of Enzymes in Purified mRNA

[0104] Unless otherwise described, standard Coomassie-stained protein gels were performed to determine the presence of any residual reagent enzymes present before and after purifications. In some instances, BCA assays were performed as well.

Assessment of mRNA Integrity via Agarose Gel Electrophoresis Assays

[0105] Unless otherwise described, messenger RNA size and integrity were assessed via gel electrophoresis. Either self-poured 1.0% agarose gel or Invitrogen E-Gel precast 1.2% agarose gels were employed. Messenger RNA was loaded at 1.0-1.5 ug quantities per well. Upon completion, messenger RNA bands were visualized using ethidium bromide.

In Vitro mRNA Integrity Assays

[0106] Unless otherwise described, i*n vitro* transfections of firefly luciferase mRNA were performed using HEK293T cells. Transfections of one microgram of each mRNA construct were performed in separate wells using lipofectamine. Cells were harvested at select time points (e.g. 4 hour, 8 hour, etc.) and respective protein production was analyzed. For FFL mRNA, cell lysates were analyzed for luciferase production via bioluminescence assays.

Bioluminescence Analysis

[0107] In examples including a fluorescent assessment of provided RNA, the bioluminescence assay was conducted using a Promega Luciferase Assay System (Item # E1500), unless otherwise specified. The Luciferase Assay Reagent was prepared by adding 10 mL of Luciferase Assay Buffer to Luciferase Assay Substrate and mix via vortex. Approximately 20 uL of homogenate samples were loaded onto a 96-well plate followed by 20 uL of plate control to each sample. Separately, 120 uL of Luciferase Assay Reagent (prepared as described above) was added to each well of a 96-well flat bottomed plate. Each plate was then inserted into the appropriate chambers using a Molecular Device Flex Station instrument and measure the luminescence (measured in relative light units (RLU)).

Example 3. Generation and Purification of Firefly Luciferase (FFL) Messenger RNA (mRNA)

[0108] This example illustrates that, according to various embodiments, a combination of tangential flow filtration (TFF) and a denaturing agent may be used according to provided methods to product a highly purified mRNA product. In this example, urea is used as the protein denaturing agent.

[0109] In this example, a five milligram batch of firefly luciferase (FFL) RNA (SEQ ID NO: 1, below) was transcribed via the *in vitro* methods described above to produce the aforementioned intermediate construct with no cap and no polyA tail. This reaction maintained a total volume of 2.24 mL and was quenched upon completion by an equivalent volume of 10M urea, bringing the final urea concentration to 5M. The resultant solution was incubated for five minutes at room temperature and transferred to the tangential flow filtration (TFF) system reservoir. The sample was diluted to 200 mL with nuclease free water and washed with 1200 mL nuclease free water by ultrafiltration of 200 mL at a time. Following this, the sample was treated with 200 mL 10mM Sodium Citrate (pH 6.4) followed by 600ml wash with nuclease free water. Finally the sample was concentrated to ~2 mL and the final concentration was determined via absorption at 260 nm (λ_{max}).

Codon-Optimized Firefly Luciferase (FFL) mRNA (SEQ ID NO: 1)

X_2AUGGAAGAUGCCAAAAACAUUAAGAAGGGCCCAGCGCCAUUCUACCCACUCGA
AGACGGGACCGCCGGCGAGCAGCUGCACAAAGCCAUGAAGCGCUACGCCCUGGUG
CCCGGCACCAUCGCCUUUACCGACGCACAUAUCGAGGUGGACAUUACCUACGCCG
AGUACUUCGAGAUGAGCGUUCGGCUGGCAGAAGCUAUGAAGCGCUAUGGGCUGA
AUACAAACCAUCGGAUCGUGGUGUGCAGCGAGAAUAGCUUGCAGUUCUUCAUGC
CCGUGUUGGGUGCCCUGUUCAUCGGUGUGGCUGUGGCCCCAGCUAACGACAUCUA
CAACGAGCGCGAGCUGCUGAACAGCAUGGGCAUCAGCCAGCCCACCGUCGUAUUC
GUGAGCAAGAAAGGGCUGCAAAAGAUCCUCAACGUGCAAAAGAAGCUACCGAUC
AUACAAAAGAUCAUCAUCAUGGAUAGCAAGACCGACUACCAGGGCUUCCAAAGCA
UGUACACCUUCGUGACUUCCCAUUUGCCACCCGGCUUCAACGAGUACGACUUCGU
GCCCGAGAGCUUCGACCGGGACAAAACCAUCGCCCUGAUCAUGAACAGUAGUGGC
AGUACCGGAUUGCCCAAGGGCGUAGCCCUACCGCACCGCACCGCUUGUGUCCGAU
UCAGUCAUGCCCGCGACCCCAUCUUCGGCAACCAGAUCAUCCCCGACACCGCUAU
CCUCAGCGUGGUGCCAUUUCACCACGGCUUCGGCAUGUUCACCACGCUGGGCUAC
UUGAUCUGCGGCUUUCGGGUCGUGCUCAUGUACCGCUUCGAGGAGGAGCUAUUC
UUGCGCAGCUUGCAAGACUAUAAGAUUCAAUCUGCCCUGCUGGUGCCCACACUAU
UUAGCUUCUUCGCUAAGAGCACUCUCAUCGACAAGUACGACCUAAGCAACUUGCA
CGAGAUCGCCAGCGGCGGGGCGCCGCUCAGCAAGGAGGUAGGUGAGGCCGUGGCC
AAACGCUUCCACCUACCAGGCAUCCGCCAGGGCUACGGCCUGACAGAAACAACCA
GCGCCAUUCUGAUCACCCCCGAAGGGGACGACAAGCCUGGCGCAGUAGGCAAGGU
GGUGCCCUUCUUCGAGGCUAAGGUGGUGGACUUGGACACCGGUAAGACACUGGG
UGUGAACCAGCGCGGCGAGCUGUGCGUCCGUGGCCCCAUGAUCAUGAGCGGCUAC
GUUAACAACCCCGAGGCUACAAACGCUCUCAUCGACAAGGACGGCUGGCUGCACA
GCGGCGACAUCGCCUACUGGGACGAGGACGAGCACUUCUUCAUCGUGGACCGGCU
GAAGAGCCUGAUCAAAUACAAGGGCUACCAGGUAGCCCCAGCCGAACUGGAGAGC
AUCCUGCUGCAACACCCCAACAUCUUCGACGCCGGGGUCGCCGGCCUGCCCGACG
ACGAUGCCGGCGAGCUGCCCGCCGCAGUCGUCGUGCUGGAACACGGUAAAACCAU
GACCGAGAAGGAGAUCGUGGACUAUGUGGCCAGCCAGGUUACAACCGCCAAGAA
GCUGCGCGGUGGUGUUGUGUUCGUGGACGAGGUGCCUAAAGGACUGACCGGCAA
GUUGGACGCCCGCAAGAUCCGCGAGAUUCUCAUUAAGGCCAAGAAGGGCGGCAAG
AUCGCCGUGUA**Y_2**

5’ and 3’ UTR Sequences:

X_2 =
GGGAUCCUACC (SEQ ID NO: 2)

Y_2 =
UUUGAAUU (SEQ ID NO: 3)

[0110] Approximately 5mg of TFF-purified firefly luciferase RNA was capped and tailed in a final reaction volume of 9mL, as described above. A portion of this reaction mixture (6.7ml) was treated with 5M urea for 5 minutes at room temperature (RT) and purified using TFF. Approximately 1.5 mg of the cap/tail reaction mixture was purified via TFF using solely water and isolated. Separately, another small portion of the cap/tail reaction mixture was purified using a Qiagen RNeasy Purification kit according to published protocol. The three isolated final FFL mRNA batches were aliquotted and transfected into HEK293T cells as described below. Cell lysates were analyzed for the presence of FFL protein via fluorescence detection (FFL activity).

[0111] In this example, in order to remove reaction enzymes in this example, a portion of the FFL mRNA IVT reaction mixture was subjected to 10M urea resulting in a final concentration of 5M urea. This solution was incubated for five minutes at room temperature and then purified via TFF as described above. Figure 1 shows a coomassie stained protein gel which shows the resulting mRNA isolated after TFF employing the aforementioned urea conditions. There is no detectable enzyme present upon completion.

[0112] After producing the capped and tailed FFL mRNA product, TFF methods were employed further to purify the final target mRNA. Portions of the same cap/tail reaction mixture were separately aliquotted and purified either via TFF with no urea or via spin-column methods (Qiagen RNeasy Kit) for comparison. A comparison of the final mRNA isolated either by TFF or spin column was made using gel electrophoresis and is depicted in Figure 2. Further, residual enzyme levels were monitored via protein gel (Figure 3). In Figure 2, one can clearly see the respective "IVT" FFL mRNA bands migrating at ~1900 nt with the capped & tailed (C/T) final mRNA approximately 2100 nt long. The "shortmer" band typically observed using spin-column isolation after the cap/tail step is indeed observed in Lane 4.

[0113] It is apparent that the shortmer band is not present after the cap/tail step when TFF-purified mRNA is employed. While substantial amounts of enzyme reagents can be removed using either purification method, shortmer impurities cannot. This demonstrated that the tangential flow filtration methods described herein are a successful and efficient method for purification of prematurely aborted sequences during mRNA transcription.

[0114] In order to determine whether provided mRNA can be translated into the desired protein, a comparison of each of the isolated FFL mRNA constructs (TFF vs spin-column) was made. Each of the three constructs listed below were transfected into HEK293T cells and corresponding FFL protein production was assessed via FFL protein activity in the form of FFL luminescence upon exposure to luciferin (*vida supra*).

FFL Constructs:

1. FFL IVT purified via TFF (urea) and C/T step via TFF (no urea)
2. FFL IVT purified via TFF (urea) and C/T step via TFF (urea)
3. FFL IVT purified via spin column and C/T step via spin column

[0115] A comparison of luminescence output of FFL protein produced from each is represented in Figure 4. The integrity of the TFF-purified FFL mRNA is maintained throughout the tangential flow filtration process under the conditions described (exposure to 5M urea).

Example 4. Generation and Purification of Factor IX (FIX) mRNA

[0116] This example further illustrates that, according to various embodiments, a combination of tangential flow filtration (TFF) and a denaturing agent may be used according to provided methods to product a highly purified mRNA product. In this example, guanidinium thiocyanate is used as the protein denaturing agent.

[0117] In this example, a second species of mRNA was produced and purified, this time coding for Factor IX (SEQ ID NO: 4, below). Initially, a five milligram batch of Factor IX (FIX) RNA was transcribed via *in vitro* methods as described above to produce the aforementioned RNA with no cap and no polyA tail. This reaction maintained a total volume of 2.24 mL and was quenched upon completion by the addition of Proteinase K (4mg/ml IVT reaction) which was incubated in the reaction mixture at 37°C for 5 minutes. Upon completion, 6M guanidinium thiocyanate (4.3 mL, final ~4M) was added and the resultant solution was incubated for five minutes at room temperature and transferred to the TFF system reservoir. The

sample was diluted to 200 mL with nuclease free water and washed with 1600 mL nuclease free water by ultrafiltration of 200 mL at a time. Upon completion, the sample was concentrated to ~2 mL and the final concentration was determined via absorption at 260 nm (λ_{max}).

Human Factor IX (FIX) mRNA (SEQ ID NO: 4)

X_1AUGCAGCGCGUGAACAUGAUCAUGGCAGAAUCACCAGGCCUCAUCACCAUCUG
CCUUUUAGGAUAUCUACUCAGUGCUGAAUGUACAGUUUUUCUUGAUCAUGAAAA
CGCCAACAAAAUUCUGAGGCGGAGAAGGAGGUAUAAUUCAGGUAAAUUGGAAGA
GUUUGUUCAAGGGAACCUUGAGAGAGAAUGUAUGGAAGAAAAGUGUAGUUUUGA
AGAAGCACGAGAAGUUUUUGAAAACACUGAAAGAACAACUGAAUUUUGGAAGCA
GUAUGUUGAUGGAGAUCAGUGUGAGUCCAAUCCAUGUUUAAAUGGCGGCAGUUG
CAAGGAUGACAUUAAUUCCUAUGAAUGUUGGUGUCCCUUUGGAUUUGAAGGAAA
GAACUGUGAAUUAGAUGUAACAUGUAACAUUAAGAAUGGCAGAUGCGAGCAGUU
UUGUAAAAAUAGUGCUGAUAACAAGGUGGUUUGCUCCUGUACUGAGGGAUAUCG
ACUUGCAGAAAACCAGAAGUCCUGUGAACCAGCAGUGCCAUUUCCAUGUGGAAG
AGUUUCUGUUUCACAAACUUCUAAGCUCACCCGUGCUGAGGCUGUUUUUCCUGAU
GUGGACUAUGUAAAUUCUACUGAAGCUGAAACCAUUUUGGAUAACAUCACUCAA
AGCACCCAAUCAUUUAAUGACUUCACUCGGGUUGUUGGUGGAGAAGAUGCCAAA
CCAGGUCAAUUCCCUUGGCAGGUUGUUUUGAAUGGUAAAGUUGAUGCAUUCUGU
GGAGGCUCUAUCGUUAAUGAAAAAUGGAUUGUAACUGCUGCCCACUGUGUUGAA
ACUGGUGUUAAAAUUACAGUUGUCGCAGGUGAACAUAAUAUUGAGGAGACAGAA
CAUACAGAGCAAAAGCGAAAUGUGAUUCGAAUUAUUCCUCACCACAACUACAAU
GCAGCUAUUAAUAAGUACAACCAUGACAUUGCCCUUCUGGAACUGGACGAACCCU
UAGUGCUAAACAGCUACGUUACACCUAUUUGCAUUGCUGACAAGGAAUACACGA
ACAUCUUCCUCAAAUUUGGAUCUGGCUAUGUAAGUGGCUGGGGAAGAGUCUUCC
ACAAAGGGAGAUCAGCUUUAGUUCUUCAGUACCUUAGAGUUCCACUUGUUGACC
GAGCCACAUGUCUUCGAUCUACAAAGUUCACCAUCUAUAACAACAUGUUCUGUGC
UGGCUUCCAUGAAGGAGGUAGAGAUUCAUGUCAAGGAGAUAGUGGGGGACCCCA
UGUUACUGAAGUGGAAGGGACCAGUUUCUUAACUGGAAUUAUUAGCUGGGGUGA
AGAGUGUGCAAUGAAAGGCAAAUAUGGAAUAUAUACCAAGGUAUCCCGGUAUGU
CAACUGGAUUAAGGAAAAAACAAAGCUCACUUAA**Y_1**

5' and 3' UTR Sequences:

X_1 =
GGACAGAUCGCCUGGAGACGCCAUCCACGCUGUUUUGACCUCCAUAGAAGACACC
GGGACCGAUCCAGCCUCCGCGGCCGGGAACGGUGCAUUGGAACGCGGAUUCCCCG
UGCCAAGAGUGACUCACCGUCCUUGACACG *(SEQ ID NO: 5)*

Y_1 =

CGGGUGGCAUCCCUGUGACCCCUCCCCAGUGCCUCUCCUGGCCCUGGAAGUUGCC ACUCCAGUGCCCACCAGCCUUGUCCUAAUAAAAUUAAGUUGCAUC *(SEQ ID NO: 6)*

[0118] The above method was also performed as described above, with the addition of actinomycin D (10 μg/ml IVT reaction) during the Proteinase K step. By quenching the IVT reaction with Proteinase K (with or without actinomycin D), one can also successfully achieve removal of all enzymes (Figure 5). While Proteinase K may facilitate removal, large scale manufacturing of an mRNA drug substance would require this enzyme to be made at large scale incurring additional unnecessary costs, and therefore may not be a desired approach in some embodiments. As shown in Figure 6, FIX mRNA produced as described above (with and without actinomycin D), as well as FIX mRNA purified using 5M urea, does not contain detectable levels of shortmers, similar to the results for FFL mRNA as described in Example 3.

Example 5. Generation and Purification of Cystic Fibrosis Transmembrane Conductance Regulator (CFTR) mRNA

[0119] This example further illustrates that, according to various embodiments, a combination of tangential flow filtration (TFF) and a denaturing agent may be used according to provided methods to product a highly purified mRNA product. In this example, potassium chloride is used as the protein denaturing agent.

[0120] In this example, a third species of mRNA was produced and purified, this time coding for the Cystic Fibrosis Transmembrane Conductance Regulator (CFTR, SEQ ID NO: 7, below). Initially, a five milligram batch of CFTR RNA was transcribed via *in vitro* methods as described above to produce the aforementioned RNA with no cap and no polyA tail. This reaction maintains a total volume of 2.24 mL and was quenched upon completion by addition of 2M KCl (~200 mL). The resultant solution was incubated for five minutes at room temperature and transferred to the TFF system reservoir. The sample was diafiltrated at a constant volume of 200 mL with 2M KCL in nuclease-free water for three to four diavolumes. After this time, the resultant solution was washed with 400 mL nuclease-free water by ultrafiltration of 200 mL at a

time. Following this, the sample was treated with 200 mL 1 mM Sodium Citrate (pH6.4) followed by 600ml wash with nuclease free water. Finally, the sample was concentrated to ~2 mL and the final concentration was determined via absorption at 260 nm (λ_{max}).

Codon-Optimized Cystic Fibrosis Transmembrane Conductance Regulator (CFTR) mRNA (SEQ ID NO: 7)

$\mathbf{X_1}$AUGCAGCGGUCCCCGCUCGAAAAGGCCAGUGUCGUGUCCAAACUCUUCUUCUC
AUGGACUCGGCCUAUCCUUAGAAAGGGGUAUCGGCAGAGGCUUGAGUUGUCUGA
CAUCUACCAGAUCCCCUCGGUAGAUUCGGCGGAUAACCUCUCGGAGAAGCUCGAA
CGGGAAUGGGACCGCGAACUCGCGUCUAAGAAAAACCCGAAGCUCAUCAACGCAC
UGAGAAGGUGCUUCUUCUGGCGGUUCAUGUUCUACGGUAUCUUCUUGUAUCUCG
GGGAGGUCACAAAAGCAGUCCAACCCCUGUUGUUGGGUCGCAUUAUCGCCUCGUA
CGACCCCGAUAACAAAGAAGAACGGAGCAUCGCGAUCUACCUCGGGAUCGGACUG
UGUUUGCUUUUCAUCGUCAGAACACUUUUGUUGCAUCCAGCAAUCUUCGGCCUCC
AUCACAUCGGUAUGCAGAUGCGAAUCGCUAUGUUUAGCUUGAUCUACAAAAAGA
CACUGAAACUCUCGUCGCGGGUGUUGGAUAAGAUUUCCAUCGGUCAGUUGGUGU
CCCUGCUUAGUAAUAACCUCAACAAAUUCGAUGAGGGACUGGCGCUGGCACAUUU
CGUGUGGAUUGCCCCGUUGCAAGUCGCCCUUUUGAUGGGCCUUAUUUGGGAGCU
GUUGCAGGCAUCUGCCUUUUGUGGCCUGGGAUUUCUGAUUGUGUUGGCAUUGUU
UCAGGCUGGGCUUGGGCGGAUGAUGAUGAAGUAUCGCGACCAGAGAGCGGGUAA
AAUCUCGGAAAGACUCGUCAUCACUUCGGAAAUGAUCGAAAACAUCCAGUCGGUC
AAAGCCUAUUGCUGGGAAGAAGCUAUGGAGAAGAUGAUUGAAAACCUCCGCCAA
ACUGAGCUGAAACUGACCCGCAAGGCGGCGUAUGUCCGGUAUUUCAAUUCGUCAG
CGUUCUUCUUUUCCGGGUUCUUCGUUGUCUUUCUCUCGGUUUUGCCUUAUGCCUU
GAUUAAGGGGAUUAUCCUCCGCAAGAUUUUCACCACGAUUUCGUUCUGCAUUGU
AUUGCGCAUGGCAGUGACACGGCAAUUUCCGUGGGCCGUGCAGACAUGGUAUGA
CUCGCUUGGAGCGAUCAACAAAAUCCAAGACUUCUUGCAAAAGCAAGAGUACAA
GACCCUGGAGUACAAUCUUACUACUACGGAGGUAGUAAUGGAGAAUGUGACGGC
UUUUUGGGAAGAGGGUUUUGGAGAACUGUUUGAGAAAGCAAAGCAGAAUAACAA
CAACCGCAAGACCUCAAAUGGGGACGAUUCCCUGUUUUUCUCGAACUUCUCCCUG
CUCGGAACACCCGUGUUGAAGGACAUCAAUUUCAAGAUUGAGAGGGGACAGCUU
CUCGCGGUAGCGGGAAGCACUGGUGCGGGAAAAACUAGCCUCUUGAUGGUGAUU
AUGGGGGAGCUUGAGCCCAGCGAGGGGAAGAUUAAACACUCCGGGCGUAUCUCA
UUCUGUAGCCAGUUUUCAUGGAUCAUGCCCGGAACCAUUAAAGAGAACAUCAUU
UUCGGAGUAUCCUAUGAUGAGUACCGAUACAGAUCGGUCAUUAAGGCGUGCCAG
UUGGAAGAGGACAUUUCUAAGUUCGCCGAGAAGGAUAACAUCGUCUUGGGAGAA
GGGGGUAUUACAUUGUCGGGAGGGCAGCGAGCGCGGAUCAGCCUCGCGAGAGCG
GUAUACAAAGAUGCAGAUUUGUAUCUGCUUGAUUCACCGUUUGGAUACCUCGAC
GUAUUGACAGAAAAAGAAAUCUUCGAGUCGUGCGUGUGUAAACUUAUGGCUAAU
AAGACGAGAAUCCUGGUGACAUCAAAAAUGGAACACCUUAAGAAGGCGGACAAG
AUCCUGAUCCUCCACGAAGGAUCGUCCUACUUUUACGGCACUUUCUCAGAGUUGC
AAAACUUGCAGCCGGACUUCUCAAGCAAACUCAUGGGGUGUGACUCAUUCGACCA

GUUCAGCGCGGAACGGCGGAACUCGAUCUUGACGGAAACGCUGCACCGAUUCUCG
CUUGAGGGUGAUGCCCCGGUAUCGUGGACCGAGACAAAGAAGCAGUCGUUUAAG
CAGACAGGAGAAUUUGGUGAGAAAAGAAAGAACAGUAUCUUGAAUCCUAUUAAC
UCAAUUCGCAAGUUCUCAAUCGUCCAGAAAACUCCACUGCAGAUGAAUGGAAUU
GAAGAGGAUUCGGACGAACCCCUGGAGCGCAGGCUUAGCCUCGUGCCGGAUUCAG
AGCAAGGGGAGGCCAUUCUUCCCCGGAUUUCGGUGAUUUCAACCGGACCUACACU
UCAGGCGAGGCGAAGGCAAUCCGUGCUCAACCUCAUGACGCAUUCGGUAAACCAG
GGGCAAAACAUUCACCGCAAAACGACGGCCUCAACGAGAAAAGUGUCACUUGCAC
CCCAGGCGAAUUUGACUGAACUCGACAUCUACAGCCGUAGGCUUUCGCAAGAAAC
CGGACUUGAGAUCAGCGAAGAAAUCAAUGAAGAAGAUUUGAAAGAGUGUUUCUU
UGAUGACAUGGAAUCAAUCCCAGCGGUGACAACGUGGAACACAUACUUGCGUUA
CAUCACGGUGCACAAGUCCUUGAUUUUCGUCCUCAUCUGGUGUCUCGUGAUCUUU
CUCGCUGAGGUCGCAGCGUCACUUGUGGUCCUCUGGCUGCUUGGUAAUACGCCCU
UGCAAGACAAAGGCAAUUCUACACACUCAAGAAACAAUUCCUAUGCCGUGAUUA
UCACUUCUACAAGCUCGUAUUACGUGUUUUACAUCUACGUAGGAGUGGCCGACAC
UCUGCUCGCGAUGGGUUUCUUCCGAGGACUCCCACUCGUUCACACGCUUAUCACU
GUCUCCAAGAUUCUCCACCAUAAGAUGCUUCAUAGCGUACUGCAGGCUCCCAUGU
CCACCUUGAAUACGCUCAAGGCGGGAGGUAUUUUGAAUCGCUUCUCAAAAGAUA
UUGCAAUUUUGGAUGACCUUCUGCCCCUGACGAUCUUCGACUUCAUCCAGUUGUU
GCUGAUCGUGAUUGGGGCUAUUGCAGUAGUCGCUGUCCUCCAGCCUUACAUUUU
UGUCGCGACCGUUCCGGUGAUCGUGGCGUUUAUCAUGCUGCGGGCCUAUUUCUUG
CAGACGUCACAGCAGCUUAAGCAACUGGAGUCUGAAGGGAGGUCGCCUAUCUUU
ACGCAUCUUGUGACCAGUUUGAAGGGAUUGUGGACGUUGCGCGCCUUUGGCAGG
CAGCCCUACUUUGAAACACUGUUCCACAAAGCGCUGAAUCUCCAUACGGCAAAUU
GGUUUUUGUAUUUGAGUACCCUCCGAUGGUUUCAGAUGCGCAUUGAGAUGAUUU
UUGUGAUCUUCUUUAUCGCGGUGACUUUUAUCUCCAUCUUGACCACGGGAGAGG
GCGAGGGACGGGUCGGUAUUAUCCUGACACUCGCCAUGAACAUUAUGAGCACUU
UGCAGUGGGCAGUGAACAGCUCGAUUGAUGUGGAUAGCCUGAUGAGGUCCGUUU
CGAGGGUCUUUAAGUUCAUCGACAUGCCGACGGAGGGAAAGCCCACAAAAAGUA
CGAAACCCUAUAAGAAUGGGCAAUUGAGUAAGGUAAUGAUCAUCGAGAACAGUC
ACGUGAAGAAGGAUGACAUCUGGCCUAGCGGGGGUCAGAUGACCGUGAAGGACC
UGACGGCAAAAUACACCGAGGGAGGGAACGCAAUCCUUGAAAACAUCUCGUUCA
GCAUUAGCCCCGGUCAGCGUGUGGGGUUGCUCGGGAGGACCGGGUCAGGAAAAU
CGACGUUGCUGUCGGCCUUCUUGAGACUUCUGAAUACAGAGGGUGAGAUCCAGA
UCGACGGCGUUUCGUGGGAUAGCAUCACCUUGCAGCAGUGGCGGAAAGCGUUUG
GAGUAAUCCCCCAAAAGGUCUUUAUCUUUAGCGGAACCUUCCGAAAGAAUCUCGA
UCCUUAUGAACAGUGGUCAGAUCAAGAGAUUUGGAAAGUCGCGGACGAGGUUGG
CCUUCGGAGUGUAAUCGAGCAGUUUCCGGGAAAACUCGACUUUGUCCUUGUAGA
UGGGGGAUGCGUCCUGUCGCAUGGGCACAAGCAGCUCAUGUGCCUGGCGCGAUCC
GUCCUCUCUAAAGCGAAAAUUCUUCUCUUGGAUGAACCUUCGGCCCAUCUGGACC
CGGUAACGUAUCAGAUCAUCAGAAGGACACUUAAGCAGGCGUUUGCCGACUGCAC
GGUGAUUCUCUGUGAGCAUCGUAUCGAGGCCAUGCUCGAAUGCCAGCAAUUUCU
UGUCAUCGAAGAGAAUAAGGUCCGCCAGUACGACUCCAUCCAGAAGCUGCUUAAU
GAGAGAUCAUUGUUCCGGCAGGCGAUUUCACCAUCCGAUAGGGUGAAACUUUUU

CCACACAGAAAUUCGUCGAAGUGCAAGUCCAAACCGCAGAUCGCGGCCUUGAAAG
AAGAGACUGAAGAAGAAGUUCAAGACACGCGUCUUUAA$\mathbf{Y_1}$

5' and 3' UTR Sequences:

X_1 =
GGACAGAUCGCCUGGAGACGCCAUCCACGCUGUUUUGACCUCCAUAGAAGACACC
GGGACCGAUCCAGCCUCCGCGGCCGGGAACGGUGCAUUGGAACGCGGAUUCCCCG
UGCCAAGAGUGACUCACCGUCCUUGACACG *(SEQ ID NO: 5)*

Y_1 =
CGGGUGGCAUCCCUGUGACCCCUCCCCAGUGCCUCUCCUGGCCCUGGAAGUUGCC
ACUCCAGUGCCCACCAGCCUUGUCCUAAUAAAAUUAAGUUGCAUC *(SEQ ID NO: 6)*

[0121] In this example, in order to remove reaction enzymes, 2M KCl diafiltration was used. Exposure to large volumes of 2M KCl resulted in successful removal of all enzymes present in the reaction mixture (including T7 polymerase) as determined via protein gel electrophoresis (Figure 7). As shown via agarose gel electrophoresis, the target messenger RNA remains intact after exposure to such conditions (Figure 8).

[0122] Further, upon capping and tailing of the CFTR IVT construct, one can successfully purify the final CFTR transcript (capped and tailed) via TFF using 2M KCl. When comparing this final isolated product to the same product purified via spin-column methods, one observes a greatly diminished "shortmer" band as determined via gel electrophoresis (Figure 9).

EQUIVALENTS AND SCOPE

[0123] Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described herein. The scope of the present invention is not intended to be limited to the above Description, but rather is as set forth in the following claims:

CLAIMS

We claim:

1. A method of purifying messenger RNA (mRNA), comprising

(a) subjecting an impure preparation comprising *in vitro* synthesized mRNA to a denaturing condition; and

(b) purifying the mRNA from the impure preparation from step (a) by tangential flow filtration;

wherein the mRNA purified from step (b) is substantially free of prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis.

2. The method of claim 1, wherein step (a) comprises adding a protein denaturing agent to the impure preparation.

2a. The method of claim 2, wherein step (a) comprises incubating the impure preparation with the protein denaturing agent added at room temperature for about 5 minutes.

3. The method of claim 2 or 2a, wherein the protein denaturing agent is selected from the group consisting of urea, guanidinium thiocyanate, KCl, sodium dodecyl sulfate, sarcosyl, and combination thereof.

4. The method of any one of the preceding claims, wherein step (a) comprises adding urea to the impure preparation to achieve a resulting urea concentration of about 1 M or greater.

5. The method of claim 4, wherein the resulting urea concentration is about 2 M or greater, 3 M or greater, 4 M or greater, 5 M or greater, 6 M or greater, 7 M or greater, 8 M or greater, 9 M or greater, or 10 M or greater.

6. The method of any one of the preceding claims, wherein step (a) comprises adding guanidinium thiocyanate to the impure preparation to achieve a resulting guanidinium thiocyanate concentration of about 4 M or greater.

7. The method of claim 6, wherein the resulting guanidinium thiocyanate concentration is about 4 M or greater, 5 M or greater, 6 M or greater, 7 M or greater, 8 M or greater, 9 M or greater, or 10 M or greater.

8. The method of any one of the preceding claims, wherein step (a) comprises adding KCl to the impure preparation to achieve a resulting KCl concentration of about 1 M or greater.

9. The method of claim 8, wherein the resulting KCl concentration is about 2 M or greater, 3 M or greater, 4 M or greater, or 5 M or greater.

10. The method of any one of the preceding claims, wherein the tangential flow filtration is performed using only aqueous solvents.

11. The method of claim 10, wherein the tangential flow filtration is performed using water as solvent.

12. The method of any one of the preceding claims, wherein the mRNA purified from step (b) contains less than 1% of prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis.

13. The method of any one of the preceding claims, wherein the mRNA purified from step (b) contains less than 0.5% of prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis.

14. The method of any one of the preceding claims, wherein the mRNA purified from step (b) contains less than 0.1% of prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis.

15. The method of any one of the preceding claims, wherein the mRNA purified from step (b) contains undetectable prematurely aborted RNA sequences and/or enzyme reagents used in *in vitro* synthesis as determined by agarose gel electrophoresis or chromatographic methods.

16. The method of any one of the preceding claims, wherein the prematurely aborted RNA sequences comprise less than 15 bases.

17. The method of any one of the preceding claims, wherein the prematurely aborted RNA sequences comprise about 8-12 bases.

18. The method of any one of the preceding claims, wherein the enzyme reagents used in *in vitro* synthesis comprise T7 RNA polymerase, DNAse I, pyrophosphatase, and/or RNAse inhibitor.

19. The method of any one of the preceding claims, wherein the enzyme reagents used in *in vitro* synthesis comprise T7 RNA polymerase.

20. The method of any one of the preceding claims, wherein the tangential flow filtration is performed before a cap and poly-A tail are added to the *in vitro* synthesized mRNA.

21. The method of any one of claims 1-19, wherein the tangential flow filtration is performed after a cap and poly-A tail are added to the *in vitro* synthesized mRNA.

22. The method of any one of claims 1-19, wherein the tangential flow filtration is performed both before and after a cap and poly-A tail are added to the *in vitro* synthesized mRNA.

23. The method of any one of the preceding claims, wherein the *in vitro* synthesized mRNA is greater than about 1 kb, 1.5 kb, 2 kb, 2.5 kb, 3 kb, 3.5 kb, 4 kb, 4.5 kb, or 5 kb in length.

24. The method of any one of the preceding claims, wherein the *in vitro* synthesized mRNA comprises one or more modifications to enhance stability.

25. The method of claim 24, wherein the one or more modifications are selected from modified nucleotide, modified sugar phosphate backbones, 5' and/or 3' untranslated region.

26. The method of any one of claims 1-23, wherein the *in vitro* synthesized mRNA is unmodified.

27. The method of any one of the preceding claims, wherein the mRNA purified from step (b) has an integrity greater than 95%.

28. The method of any one of the preceding claims, wherein the mRNA purified from step (b) has an integrity greater than 98%.

29. The method of any one of the preceding claims, wherein the mRNA purified from step (b) has an integrity greater than 99%.

30. A method for manufacturing messenger RNA (mRNA) comprising:

synthesizing mRNA *in vitro*; and

purifying the *in vitro* synthesized mRNA using a method according to any one of the preceding claims.

31. A messenger RNA (mRNA) purified using a method according to any one of the preceding claims.