

Stabilized soluble pre-fusion RSV F polypeptides

The present invention relates to the field of medicine. The invention in particular relates to recombinant pre-fusion RSV F polypeptides and uses thereof, e.g. in immunogenic compositions.

Background of the invention

After discovery of the respiratory syncytial virus (RSV) in the 1950s, the virus soon became a recognized pathogen associated with lower and upper respiratory tract infections in humans. Worldwide, it is estimated that 64 million RSV infections occur each year resulting in 160.000 deaths (WHO Acute Respiratory Infections Update September 2009). The most severe disease occurs particularly in premature infants, the elderly and immunocompromised individuals. In children younger than 2 years, RSV is the most common respiratory tract pathogen, accounting for approximately 50% of the hospitalizations due to respiratory infections, and the peak of hospitalization occurs at 2-4 months of age. It has been reported that almost all children have been infected by RSV by the age of two. Repeated infection during lifetime is attributed to ineffective natural immunity. In the elderly, the RSV disease burden is similar to those caused by non-pandemic influenza A infections.

RSV is a paramyxovirus, belonging to the subfamily of pneumoviridae. Its genome encodes for various proteins, including the membrane proteins known as RSV Glycoprotein (G) and RSV fusion (F) protein which are the major antigenic targets for neutralizing antibodies. Antibodies against the fusion-mediating part of the F1 protein can prevent virus uptake in the cell and thus have a neutralizing effect.

A vaccine against RSV infection is currently not available, but is desired due to the high disease burden. The RSV fusion glycoprotein (RSV F) is an attractive vaccine antigen since as stated above it is the principal target of neutralizing antibodies in human sera. Indeed, a neutralizing monoclonal antibody against RSV F (Palivizumab) can prevent severe disease and
5 has been approved for prophylaxis in infants.

RSV F fuses the viral and host-cell membranes by irreversible protein refolding from the labile pre-fusion conformation to the stable post-fusion conformation. Structures of both conformations have been determined for RSV F (McLellan JS, *et al. Science* **342**, 592-598 (2013); McLellan JS, *et al. Nat Struct Mol Biol* **17**, 248-250 (2010); McLellan JS, *et al. Science*
10 **340**, 1113-1117 (2013); Swanson KA, *et al. Proceedings of the National Academy of Sciences of the United States of America* **108**, 9619-9624 (2011)), as well as for the fusion proteins from related paramyxoviruses, providing insight into the mechanism of this complex fusion machine. Like other type I fusion proteins, the inactive precursor, RSV F₀, requires cleavage during intracellular maturation by a furin-like protease. RSV F contains two furin sites, which leads to
15 three polypeptides: F2, p27 and F1, with the latter containing a hydrophobic fusion peptide (FP) at its N-terminus. In order to refold from the pre-fusion to the post-fusion conformation, the refolding region 1 (RR1) between residue 137 and 216, that includes the FP and heptad repeat A (HRA) has to transform from an assembly of helices, loops and strands to a long continuous helix. The FP, located at the N-terminal segment of RR1, is then able to extend away from the
20 viral membrane and insert into the proximal membrane of the target cell. Next, the refolding region 2 (RR2), which forms the C-terminal stem in the pre-fusion F spike and includes the heptad repeat B (HRB), relocates to the other side of the RSV F head and binds the HRA coiled-coil trimer with the HRB domain to form the six-helix bundle. The formation of the RR1 coiled-

coil and relocation of RR2 to complete the six-helix bundle are the most dramatic structural changes that occur during the refolding process.

Most neutralizing antibodies in human sera are directed against the pre-fusion conformation, but due to its instability the pre-fusion conformation has a propensity to
5 prematurely refold into the post-fusion conformation, both in solution and on the surface of the virions. An RSV F protein that has both high expression levels and maintains a stable pre-fusion conformation would be a promising candidate for use in a subunit or vector-based vaccine against RSV.

10 **Summary of the invention**

The present invention provides stable, recombinant, pre-fusion respiratory syncytial virus (RSV) fusion (F) polypeptides, i.e. recombinant RSV F polypeptides that are stabilized in the pre-fusion conformation. The RSV F polypeptides of the invention comprise at least one epitope that is specific to the pre-fusion conformation F protein. In certain embodiments, the pre-fusion
15 RSV F polypeptides are soluble polypeptides. The invention also provides nucleic acid molecules encoding the pre-fusion RSV F polypeptides according to the invention and vectors comprising such nucleic acid molecules.

The invention also relates to compositions, preferably immunogenic compositions, comprising a RSV F polypeptide, a nucleic acid molecule and/or a vector, and to the use thereof
20 in inducing an immune response against RSV F protein, in particular the use thereof as a vaccine. The invention also relates to methods for inducing an anti-respiratory syncytial virus (RSV) immune response in a subject, comprising administering to the subject an effective amount of a pre-fusion RSV F polypeptide, a nucleic acid molecule encoding said RSV F polypeptide, and/or

a vector comprising said nucleic acid molecule. Preferably, the induced immune response is characterized by neutralizing antibodies to RSV and/or protective immunity against RSV. In particular aspects, the invention relates to a method for inducing neutralizing anti-respiratory syncytial virus (RSV) F protein antibodies in a subject, comprising administering to the subject
5 an effective amount of an immunogenic composition comprising a pre-fusion RSV F polypeptide, a nucleic acid molecule encoding said RSV F polypeptide, and/or a vector comprising said nucleic acid molecule.

Brief description of the Figures

10 FIG.1. Purification of protein F(A2) KN66EI I76V L203I S215P. A) Chromatogram of elution from cation-exchange column. Blue trace is absorbance at 280nm, brown trace is conductivity. The arrow indicates the collected peak that was eluted at 15% elution step. B) Superdex200 gel filtration chromatogram of the eluate from the ion-exchange column. Blue trace is absorbance at 280nm, brown trace is conductivity. The arrows indicate the collected
15 peak.

FIG.2. A) SDS-PAGE analysis of the F(A2) KN66EI I76V L203I S215P (A) and F(A2) K66E I76V L203I S215P (B) protein sample containing peak from the SEC chromatogram under reducing and non-reducing conditions. F1, F2 fragments in reduced sample and F1+F2 in non-reduced sample are indicated. C) NativePAGE of F(A2) KN66EI I76V S215P with and without
20 L203I and F(A2) K66E I76V L203I S215P. Native marker indicates relative electrophoretic mobility of the protein but cannot be used for determination of protein molecular weight. The position of the band between 242 and 480 kDa corresponds to the position of trimeric RSV F protein (indicated by an arrow). The gels are stained with Coomassie Brilliant Blue.

FIG. 3. Additional substitution of Leu 203 to Ile increases pre-fusion F stability in the metastable pre-fusion F protein with an S215P substitution. Pre-fusion RSV F concentrations in cell culture supernatants were tested on the day of harvest (72 hours post transfection = day 1) and after storage for 5 and 15 days at 4 °C.

5 FIG. 4. Temperature stability of proteins with L203I. Melting temperature (T_m) was determined in purified protein samples by DSF.

FIG 5: SDS-PAGE analysis of the purified F proteins comprising L203I mutation under reducing (R) and non-reducing (NR) conditions. F1, F2 fragments in reduced sample and F1+F2 in non-reduced sample are indicated. The gel was stained with Coomassie Brilliant Blue.

10 FIG 6: SEC-MALS analysis of the purified F proteins comprising L203I mutation: A: F(A2)-KN66EI-I76V-I203L-S215P-D486N; B: F(A2)-K66E-I76V-I203L-S215P-D486N.

Detailed description of the invention

The fusion protein (F) of the respiratory syncytial virus (RSV) is involved in fusion of
15 the viral membrane with a host cell membrane, which is required for viral infection. The RSV F mRNA is translated into a 574 amino acid precursor protein designated F0, which contains a signal peptide sequence at the N-terminus (e.g. amino acid residues 1-26 of SEQ ID NO: 13) that is removed by a signal peptidase in the endoplasmic reticulum. F0 is cleaved at two sites (between amino acid residues 109/110 and 136/137) by cellular proteases (in particular furin, or
20 furin-like)) removing a short glycosylated intervening sequence (also referred to a p27 region, comprising the amino acid residues 110 to 136, and generating two domains or subunits designated F1 and F2. The F1 domain (amino acid residues 137-574) contains a hydrophobic fusion peptide at its N-terminus and the C-terminus contains the transmembrane (TM) (amino acid residues 530-550) and cytoplasmic region (amino acid residues 551-574). The F2 domain

(amino acid residues 27-109) is covalently linked to F1 by two disulfide bridges. The F1-F2 heterodimers are assembled as homotrimers in the virion.

A vaccine against RSV infection is not currently available, but is desired. One potential approach to producing a vaccine is a subunit vaccine based on purified RSV F protein. However, for this approach it is desirable that the purified RSV F protein is in a conformation which resembles the conformation of the pre-fusion state of RSV F protein, that is stable over time, and can be produced in sufficient quantities. In addition, for a soluble, subunit-based vaccine, the RSV F protein needs to be truncated by deletion of the transmembrane (TM) and the cytoplasmic region to create a soluble secreted F protein (sF). Because the TM region is responsible for membrane anchoring and trimerization, the anchorless soluble F protein is considerably more labile than the full-length protein and will readily refold into the post-fusion end-state. In order to obtain soluble F protein in the stable pre-fusion conformation that shows high expression levels and high stability, the pre-fusion conformation thus needs to be stabilized. Because also the full length (membrane-bound) RSV F protein is metastable, the stabilization of the pre-fusion conformation is also desirable for any life attenuated or vector based vaccine approach.

For the stabilization of soluble RSV F, that is cleaved into the F1 and F2 subunit, in the pre-fusion conformation, a fibrin – based trimerization domain was fused to the C-terminus of the soluble RSV-F C-terminal end (McLellan et al., Nature Struct. Biol. 17: 2-248-250 (2010); McLellan et al., Science 340(6136):1113-7 (2013)). This fibrin domain or ‘Foldon’ is derived from T4 fibrin and was described earlier as an artificial natural trimerization domain (Letarov et al., Biochemistry Moscow 64: 817-823 (1993); S-Guthe et al., J. Mol. Biol. 337: 905-915. (2004)). However, the trimerization domain does not result in stable pre-fusion RSV-F protein. Moreover, these efforts have not yet resulted in candidates suitable for testing in humans.

Recently, we described combinations of several mutations that are capable of stabilizing the RSV pre-fusion F conformation (WO2014/174018 and WO2014/202570). Thus, stable pre-fusion RSVF polypeptides have been described comprising a mutation of the amino acid residue on position 67 and/or a mutation of the amino acid residue on position 215, preferably a mutation of amino acid residue N/T on position 67 into I and/or a mutation of amino acid residue S on position 215 into P. In addition, soluble pre-fusion RSV F polypeptides have been described comprising a truncated F1 domain, and at least one stabilizing mutation in the F1 and/or F2 domain as compared to the RSV F1 and/or F2 domain in the wild-type RSV F protein, wherein the polypeptide comprises a heterologous trimerization domain linked to said truncated F1 domain. Also further pre-fusion RSV F polypeptides have been described, wherein the polypeptides comprise at least one further mutation, wherein said mutation is selected from the group consisting of:

- (a) a mutation of the amino acid residue on position 46;
- (b) a mutation of the amino acid residue on position 77;
- (c) a mutation of the amino acid residue on position 80;
- (d) a mutation of the amino acid residue on position 92;
- (e) a mutation of the amino acid residue on position 175;
- (f) a mutation of the amino acid residue on position 184;
- (g) a mutation of the amino acid residue on position 185;
- (h) a mutation of the amino acid residue on position 201;
- (i) a mutation of the amino acid residue on position 209;
- (j) a mutation of the amino acid residue on position 421;
- (k) a mutation of the amino acid residue on position 426;

- (l) a mutation of the amino acid residue on position 465;
- (m) a mutation of the amino acid residue on position 486;
- (n) a mutation of the amino acid residue on position 487; and
- (o) a mutation of the amino acid residue on position 508.

5 Preferably, the at least one further mutation is selected from the group consisting of:

- (a) a mutation of the amino acid residue S on position 46 into G;
- (b) a mutation of the amino acid residue K on position 77 into E;
- (c) a mutation of the amino acid residue K on position 80 into E;
- (d) a mutation of the amino acid residue E on position 92 into D;
- 10 (e) a mutation of the amino acid residue N on position 175 into P;
- (f) a mutation of the amino acid residue G on position 184 into N;
- (g) a mutation of the amino acid residue V on position 185 into N;
- (h) a mutation of the amino acid residue K on position 201 into Q;
- (i) a mutation of the amino acid residue K on position 209 into Q;
- 15 (j) a mutation of the amino acid residue K on position 421 into N;
- (k) a mutation of the amino acid residue N on position 426 into S;
- (l) a mutation of the amino acid residue K on position 465 into E or Q;
- (m) a mutation of the amino acid residue D on position 486 into N;
- (n) a mutation of the amino acid residue E on position 487 into Q, N or I; and
- 20 (o) a mutation of the amino acid residue K on position 508 into E.

If only one of these mutations was applied (in particular the mutation S215P), a metastable protein was obtained that could be used for the evaluation of the stabilizing effect of alternative substitutions.

According to the present invention it has been found that a mutation of the amino acid residue L on position 203 into I further stabilizes the protein in the pre-fusion conformation.

The present invention thus provides recombinant pre-fusion F polypeptides comprising a mutation of the amino acid residue L on position 203 into I.

5 The invention in particular provides recombinant pre-fusion respiratory syncytial virus (RSV) Fusion (F) polypeptides, wherein the polypeptide comprises at least one, preferably at least two stabilizing mutations in the F1 and/or F2 domain as compared to the RSV F1 and/or F2 domain in a wild-type RSV F protein, wherein at least one of the stabilizing mutations is a mutation of amino acid residue L on position 203 into I.

10 The invention further provides recombinant pre-fusion F polypeptides comprising a mutation of the amino acid S on position 215 into P (S215P) and a mutation of the amino acid residue L on position 203 into I.

 The present invention thus provides a new stabilization mutation to provide recombinant stable pre-fusion RSV F polypeptides, i.e. RSV F polypeptides that are stabilized in the pre-
15 fusion conformation. The stable pre-fusion RSV F polypeptides of the invention are in the pre-fusion conformation, i.e. they comprise (display) at least one epitope that is specific to the pre-fusion conformation F protein. An epitope that is specific to the pre-fusion conformation F protein is an epitope that is not presented in the post-fusion conformation. Without wishing to be bound by any particular theory, it is believed that the pre-fusion conformation of RSV F protein
20 may contain epitopes that are the same as those on the RSV F protein expressed on natural RSV virions, and therefore may provide advantages for eliciting protective neutralizing antibodies.

 In certain embodiments, the polypeptides of the invention comprise at least one epitope that is recognized by a pre-fusion specific monoclonal antibody, comprising a heavy chain CDR1

region of SEQ ID NO: 1, a heavy chain CDR2 region of SEQ ID NO: 2, a heavy chain CDR3 region of SEQ ID NO: 3 and a light chain CDR1 region of SEQ ID NO: 4, a light chain CDR2 region of SEQ ID NO: 5, and a light chain CDR3 region of SEQ ID NO: 6 (hereafter referred to as CR9501) and/or a pre-fusion specific monoclonal antibody, comprising a heavy chain CDR1
5 region of SEQ ID NO: 7, a heavy chain CDR2 region of SEQ ID NO: 8, a heavy chain CDR3 region of SEQ ID NO: 9 and a light chain CDR1 region of SEQ ID NO: 10, a light chain CDR2 region of SEQ ID NO: 11, and a light chain CDR3 region of SEQ ID NO: 12 (referred to as CR9502). CR9501 and CR9502 comprise the heavy and light chain variable regions, and thus the binding specificities, of the antibodies 58C5 and 30D8, respectively, which have previously been
10 shown to bind specifically to RSV F protein in its pre-fusion conformation and not to the post-fusion conformation (see WO2012/006596).

In certain embodiments, the recombinant pre-fusion RSV F polypeptides comprise at least one epitope that is recognized by at least one pre-fusion specific monoclonal antibody as described above and are trimeric. In certain embodiments, the stable pre-fusion RSV F
15 polypeptides according to the invention are soluble and comprise a truncated F1 domain.

It is known that RSV exists as a single serotype having two antigenic subgroups: A and B. The amino acid sequences of the mature processed F proteins of the two groups are about 93% identical. As used throughout the present application, the amino acid positions are given in reference to the sequence of RSV F protein from the A2 strain (SEQ ID NO: 13). As used in the
20 present invention, the wording "the amino acid at position "x" of the RSV F protein thus means the amino acid corresponding to the amino acid at position "x" in the RSV F protein of the RSV A2 strain of SEQ ID NO: 13. Note that, in the numbering system used throughout this application 1 refers to the N-terminal amino acid of an immature F0 protein (SEQ ID NO: 13)

When a RSV strain other than the A2 strain is used, the amino acid positions of the F protein are to be numbered with reference to the numbering of the F protein of the A2 strain of SEQ ID NO: 1 by aligning the sequences of the other RSV strain with the F protein of SEQ ID NO: 13 with the insertion of gaps as needed. Sequence alignments can be done using methods well known in the art, e.g. by CLUSTALW, Bioedit or CLC Workbench.

An amino acid according to the invention can be any of the twenty naturally occurring (or 'standard' amino acids) or variants thereof, such as e.g. D-amino acids (the D-enantiomers of amino acids with a chiral center), or any variants that are not naturally found in proteins, such as e.g. norleucine. The standard amino acids can be divided into several groups based on their properties. Important factors are charge, hydrophilicity or hydrophobicity, size and functional groups. These properties are important for protein structure and protein-protein interactions. Some amino acids have special properties such as cysteine, that can form covalent disulfide bonds (or disulfide bridges) to other cysteine residues, proline that induces turns of the polypeptide backbone, and glycine that is more flexible than other amino acids. Table 1 shows the abbreviations and properties of the standard amino acids.

It will be appreciated by a skilled person that the mutations can be made to the protein by routine molecular biology procedures. The mutations according to the invention preferably result in increased expression levels and/or increased stabilization of the pre-fusion RSV F polypeptides as compared RSV F polypeptides that do not comprise these mutation(s).

In certain embodiments, the pre-fusion RSV F polypeptides are soluble.

Thus, in certain embodiments, the pre-fusion RSV F polypeptides comprise a truncated F1 domain, wherein polypeptide comprises at least one stabilizing mutation in the F1 and/or F2 domain as compared to the RSV F1 and/or F2 domain in the wild-type RSV F protein. In certain

embodiments, the soluble pre-fusion RSV F polypeptides further comprise a heterologous trimerization domain linked to said truncated F1 domain. According to the invention, it was shown that by linking a heterologous trimerization domain to the C-terminal amino acid residue of a truncated F1 domain, combined with the stabilizing mutation(s), RSV F polypeptides are provided that show high expression and that bind to pre-fusion-specific antibodies, indicating that the polypeptides are in the pre-fusion conformation. In addition, the RSV F polypeptides are stabilized in the pre-fusion conformation, i.e. even after processing of the polypeptides they still bind to the pre-fusion specific antibodies CR9501 and/or CR9502, indicating that the pre-fusion specific epitope is retained.

In certain embodiments, the pre-fusion RSV F polypeptides comprise at least three mutations (as compared to a wild-type RV F protein).

In certain embodiments, the pre-fusion RSV F polypeptides comprise at least one further mutation selected from the group consisting of:

- (a) a mutation of the amino acid residue on position 46;
- (b) a mutation of the amino acid residue on position 67;
- (c) a mutation of the amino acid residue on position 83;
- (d) a mutation of the amino acid residue on position 92;
- (e) a mutation of the amino acid residue on position 184;
- (f) a mutation of the amino acid residue on position 207;
- (g) a mutation of the amino acid residue on position 486; and
- (h) a mutation of the amino acid residue on position 487.

In certain embodiments, the at least one further mutation is selected from the group consisting of:

- (a) a mutation of the amino acid residue S on position 46 into G;
- (b) a mutation of the amino acid residue N/T on position 67 into I;
- (c) a mutation of the amino acid residue L on position 83 into M;
- (d) a mutation of the amino acid residue E on position 92 into D;
- 5 (e) a mutation of the amino acid residue G on position 184 into N;
- (f) a mutation of the amino acid residue V on position 207 into I;
- (g) a mutation of the amino acid residue D on position 486 into N; and
- (h) a mutation of the amino acid residue E on position 487 into Q, N or I.

In certain embodiments, the polypeptides comprise at least two mutations.

10 In certain embodiments, the polypeptides comprise at least three mutations.

In certain embodiments, the polypeptides comprise at least four, five or six mutations.

In certain other embodiments, the heterologous trimerization domain comprises the amino acid sequence GYIPEAPRDGQAYVRKDGEWVLLSTFL (SEQ ID NO: 14).

As described above, in certain embodiments, the polypeptides of the invention comprise a truncated F1 domain. As used herein a “truncated” F1 domain refers to a F1 domain that is not a full length F1 domain, i.e. wherein either N-terminally or C-terminally one or more amino acid residues have been deleted. According to the invention, at least the transmembrane domain and cytoplasmic tail have been deleted to permit expression as a soluble ectodomain.

In certain other embodiments, the trimerization domain is linked to amino acid residue 513 of the RSV F1 domain. In certain embodiments, the trimerization domain comprises SEQ ID NO: 14 and is linked to amino acid residue 513 of the RSV F1 domain.

In certain embodiments, the F1 domain and/or the F domain are from an RSV A strain. In certain embodiments the F1 and/or F2 domain are from the RSV A2 strain of SEQ ID NO: 13.

In certain embodiments, the F1 domain and/or the F domain are from an RSV B strain. In certain embodiments the F1 and/or F2 domain are from the RSV B strain of SEQ ID NO: 15.

In certain embodiments, the F1 domain and/or the F domain are from an RSV CL57-v244 strain. In certain embodiments the F1 and/or F2 domain are from the RSV CL57-v244 strain of
5 SEQ ID NO: 22.

In certain embodiments, the F1 and F2 domain are from the same RSV strain. In certain embodiments, the pre-fusion RSV F polypeptides are chimeric polypeptides, i.e. comprising F1 and F2 domains that are from different RSV strains.

In certain embodiments, the pre-fusion RSV F polypeptides comprise an amino acid
10 sequence selected from the group consisting of SEQ ID NO: 20, SEQ ID NO: 21, SEQ ID NO: 23 and SEQ ID NO: 24.

In certain embodiments, the level of expression of the pre-fusion RSV F polypeptides of the invention is increased, as compared to a wild-type RSV F polypeptide. In certain
15 embodiments the level of expression is increased at least 5-fold, preferably up to 10-fold. In certain embodiments, the level of expression is increased more than 10-fold.

The pre-fusion RSV F polypeptides according to the invention are stable, i.e. do not readily change into the post-fusion conformation upon processing of the polypeptides, such as e.g. purification, freeze-thaw cycles, and/or storage etc.

In certain embodiments, the pre-fusion RSV F polypeptides according to the invention
20 have an increased stability upon storage at 4°C as compared to a RSV F polypeptide without the mutation(s). In certain embodiments, the polypeptides are stable upon storage at 4°C for at least 30 days, preferably at least 60 days, preferably at least 6 months, even more preferably at least 1 year. With “stable upon storage”, it is meant that the polypeptides still display the at least one

epitope specific for the a pre-fusion specific antibody (e.g. CR9501) upon storage of the polypeptide in solution (e.g. culture medium) at 4° C for at least 30 days, e.g. as determined using a method as described in Example 7 or 9. In certain embodiments, the polypeptides display the at least one pre-fusion specific epitope for at least 6 months, preferably for at least 1 year upon storage of the pre-fusion RSV F polypeptides at 4°C.

In certain embodiments, the pre-fusion RSV F polypeptides according to the invention have an increased stability when subjected to heat, as compared to RSV F polypeptides without said mutation(s). In certain embodiments, the pre-fusion REV F polypeptides are heat stable for at least 30 minutes at a temperature of 55° C, preferably at 58° C, more preferably at 60° C With “heat stable” it is meant that the polypeptides still display the at least one pre-fusion specific epitope after having been subjected for at least 30 minutes to an increased temperature (i.e. a temperature of 55°C or above), e.g. as determined using a method as described in Example 6.

In certain embodiments, the polypeptides display the at least one pre-fusion specific epitope after being subjected to 1 to 6 freeze-thaw cycles in an appropriate formulation buffer.

As used throughout the present application nucleotide sequences are provided from 5' to 3' direction, and amino acid sequences from N-terminus to C-terminus, as custom in the art.

In certain embodiments, the encoded polypeptides according to the invention further comprise a leader sequence, also referred to as signal sequence or signal peptide, corresponding to amino acids 1-26 of SEQ ID NO: 13. This is a short (typically 5-30 amino acids long) peptide present at the N-terminus of the majority of newly synthesized proteins that are destined towards the secretory pathway. In certain embodiments, the polypeptides according to the invention do not comprise a leader sequence.

In certain embodiments, the polypeptides comprise a HIS-Tag. A His-Tag or polyhistidine-tag is an amino acid motif in proteins that consists of at least five histidine (H) residues, often at the N- or C-terminus of the protein, which is generally used for purification purposes.

5 The present invention further provides nucleic acid molecules encoding the RSV F polypeptides according to the invention.

 In preferred embodiments, the nucleic acid molecules encoding the polypeptides according to the invention are codon-optimized for expression in mammalian cells, preferably human cells. Methods of codon-optimization are known and have been described previously (e.g. 10 WO 96/09378). A sequence is considered codon-optimized if at least one non-preferred codon as compared to a wild type sequence is replaced by a codon that is more preferred. Herein, a non-preferred codon is a codon that is used less frequently in an organism than another codon coding for the same amino acid, and a codon that is more preferred is a codon that is used more frequently in an organism than a non-preferred codon. The frequency of codon usage for a 15 specific organism can be found in codon frequency tables, such as in <http://www.kazusa.or.jp/codon>. Preferably more than one non-preferred codon, preferably most or all non-preferred codons, are replaced by codons that are more preferred. Preferably the most frequently used codons in an organism are used in a codon-optimized sequence. Replacement by preferred codons generally leads to higher expression.

20 It will be understood by a skilled person that numerous different polynucleotides and nucleic acid molecules can encode the same polypeptide as a result of the degeneracy of the genetic code. It is also understood that skilled persons may, using routine techniques, make nucleotide substitutions that do not affect the polypeptide sequence encoded by the nucleic acid

molecules to reflect the codon usage of any particular host organism in which the polypeptides are to be expressed. Therefore, unless otherwise specified, a "nucleotide sequence encoding an amino acid sequence" includes all nucleotide sequences that are degenerate versions of each other and that encode the same amino acid sequence. Nucleotide sequences that encode proteins and RNA may or may not include introns.

Nucleic acid sequences can be cloned using routine molecular biology techniques, or generated de novo by DNA synthesis, which can be performed using routine procedures by service companies having business in the field of DNA synthesis and/or molecular cloning (e.g. GeneArt, GenScripts, Invitrogen, Eurofins).

The invention also provides vectors comprising a nucleic acid molecule as described above. In certain embodiments, a nucleic acid molecule according to the invention thus is part of a vector. Such vectors can easily be manipulated by methods well known to the person skilled in the art, and can for instance be designed for being capable of replication in prokaryotic and/or eukaryotic cells. In addition, many vectors can be used for transformation of eukaryotic cells and will integrate in whole or in part into the genome of such cells, resulting in stable host cells comprising the desired nucleic acid in their genome. The vector used can be any vector that is suitable for cloning DNA and that can be used for transcription of a nucleic acid of interest. Suitable vectors according to the invention are e.g. adenovectors, alphavirus, paramyxovirus, vaccinia virus, herpes virus, retroviral vectors etc. The person skilled in the art is capable of choosing suitable expression vectors, and inserting the nucleic acid sequences of the invention in a functional manner.

Host cells comprising the nucleic acid molecules encoding the pre-fusion RSV F polypeptides form also part of the invention. The pre-fusion RSV F polypeptides may be

produced through recombinant DNA technology involving expression of the molecules in host cells, e.g. Chinese hamster ovary (CHO) cells, tumor cell lines, BHK cells, human cell lines such as HEK293 cells, PER.C6 cells, or yeast, fungi, insect cells, and the like, or transgenic animals or plants. In certain embodiments, the cells are from a multicellular organism, in certain

5 embodiments they are of vertebrate or invertebrate origin. In certain embodiments, the cells are mammalian cells. In certain embodiments, the cells are human cells. In general, the production of a recombinant proteins, such the pre-fusion RSV F polypeptides of the invention, in a host cell comprises the introduction of a heterologous nucleic acid molecule encoding the polypeptide in expressible format into the host cell, culturing the cells under conditions conducive to expression

10 of the nucleic acid molecule and allowing expression of the polypeptide in said cell. The nucleic acid molecule encoding a protein in expressible format may be in the form of an expression cassette, and usually requires sequences capable of bringing about expression of the nucleic acid, such as enhancer(s), promoter, polyadenylation signal, and the like. The person skilled in the art is aware that various promoters can be used to obtain expression of a gene in host cells.

15 Promoters can be constitutive or regulated, and can be obtained from various sources, including viruses, prokaryotic, or eukaryotic sources, or artificially designed.

Cell culture media are available from various vendors, and a suitable medium can be routinely chosen for a host cell to express the protein of interest, here the pre-fusion RSV F polypeptides. The suitable medium may or may not contain serum.

20 A “heterologous nucleic acid molecule” (also referred to herein as ‘transgene’) is a nucleic acid molecule that is not naturally present in the host cell. It is introduced into for instance a vector by standard molecular biology techniques. A transgene is generally operably linked to expression control sequences. This can for instance be done by placing the nucleic acid

encoding the transgene(s) under the control of a promoter. Further regulatory sequences may be added. Many promoters can be used for expression of a transgene(s), and are known to the skilled person, e.g. these may comprise viral, mammalian, synthetic promoters, and the like. A non-limiting example of a suitable promoter for obtaining expression in eukaryotic cells is a

5 CMV-promoter (US 5,385,839), e.g. the CMV immediate early promoter, for instance comprising nt. -735 to +95 from the CMV immediate early gene enhancer/promoter. A polyadenylation signal, for example the bovine growth hormone polyA signal (US 5,122,458), may be present behind the transgene(s). Alternatively, several widely used expression vectors are available in the art and from commercial sources, e.g. the pcDNA and pEF vector series of

10 Invitrogen, pMSCV and pTK-Hyg from BD Sciences, pCMV-Script from Stratagene, etc, which can be used to recombinantly express the protein of interest, or to obtain suitable promoters and/or transcription terminator sequences, polyA sequences, and the like.

The cell culture can be any type of cell culture, including adherent cell culture, e.g. cells attached to the surface of a culture vessel or to microcarriers, as well as suspension culture. Most

15 large-scale suspension cultures are operated as batch or fed-batch processes because they are the most straightforward to operate and scale up. Nowadays, continuous processes based on perfusion principles are becoming more common and are also suitable. Suitable culture media are also well known to the skilled person and can generally be obtained from commercial sources in large quantities, or custom-made according to standard protocols. Culturing can be done for

20 instance in dishes, roller bottles or in bioreactors, using batch, fed-batch, continuous systems and the like. Suitable conditions for culturing cells are known (see e.g. Tissue Culture, Academic Press, Kruse and Paterson, editors (1973), and R.I. Freshney, Culture of animal cells: A manual of basic technique, fourth edition (Wiley-Liss Inc., 2000, ISBN 0-471-34889-9)).

The invention further provides compositions comprising a pre-fusion RSV F polypeptide and/or a nucleic acid molecule, and/or a vector, as described above. The invention thus provides compositions comprising a pre-fusion RSV F polypeptide that displays an epitope that is present in a pre-fusion conformation of the RSV F protein but is absent in the post-fusion conformation.

5 The invention also provides compositions comprising a nucleic acid molecule and/or a vector, encoding such pre-fusion RSV F polypeptide. The invention further provides immunogenic compositions comprising a pre-fusion RSV F polypeptide, and/or a nucleic acid molecule, and/or a vector, as described above. The invention also provides the use of a stabilized pre-fusion RSV F polypeptide, a nucleic acid molecule, and/or a vector, according to the invention, for inducing
10 an immune response against RSV F protein in a subject. Further provided are methods for inducing an immune response against RSV F protein in a subject, comprising administering to the subject a pre-fusion RSV F polypeptide, and/or a nucleic acid molecule, and/or a vector according to the invention. Also provided are pre-fusion RSV F polypeptides, nucleic acid molecules, and/or vectors, according to the invention for use in inducing an immune response
15 against RSV F protein in a subject. Further provided is the use of the pre-fusion RSV F polypeptides, and/or nucleic acid molecules, and/or vectors according to the invention for the manufacture of a medicament for use in inducing an immune response against RSV F protein in a subject.

The pre-fusion RSV F polypeptides, nucleic acid molecules, or vectors of the invention
20 may be used for prevention (prophylaxis) and/or treatment of RSV infections. In certain embodiments, the prevention and/or treatment may be targeted at patient groups that are susceptible RSV infection. Such patient groups include, but are not limited to e.g., the elderly (e.g. ≥ 50 years old, ≥ 60 years old, and preferably ≥ 65 years old), the young (e.g. ≤ 5 years old,

≤ 1 year old), hospitalized patients and patients who have been treated with an antiviral compound but have shown an inadequate antiviral response.

The pre-fusion RSV F polypeptides, nucleic acid molecules and/or vectors according to the invention may be used e.g. in stand-alone treatment and/or prophylaxis of a disease or condition caused by RSV, or in combination with other prophylactic and/or therapeutic treatments, such as (existing or future) vaccines, antiviral agents and/or monoclonal antibodies.

The invention further provides methods for preventing and/or treating RSV infection in a subject utilizing the pre-fusion RSV F polypeptides, nucleic acid molecules and/or vectors according to the invention. In a specific embodiment, a method for preventing and/or treating RSV infection in a subject comprises administering to a subject in need thereof an effective amount of a pre-fusion RSV F polypeptide, nucleic acid molecule and/or a vector, as described above. A therapeutically effective amount refers to an amount of a polypeptide, nucleic acid molecule or vector, that is effective for preventing, ameliorating and/or treating a disease or condition resulting from infection by RSV. Prevention encompasses inhibiting or reducing the spread of RSV or inhibiting or reducing the onset, development or progression of one or more of the symptoms associated with infection by RSV. Amelioration as used in herein may refer to the reduction of visible or perceptible disease symptoms, viremia, or any other measurable manifestation of influenza infection.

For administering to subjects, such as humans, the invention may employ pharmaceutical compositions comprising a pre-fusion RSV F polypeptide, a nucleic acid molecule and/or a vector as described herein, and a pharmaceutically acceptable carrier or excipient. In the present context, the term "pharmaceutically acceptable" means that the carrier or excipient, at the dosages and concentrations employed, will not cause any unwanted or harmful effects in the subjects to which

they are administered. Such pharmaceutically acceptable carriers and excipients are well known in the art (see Remington's Pharmaceutical Sciences, 18th edition, A. R. Gennaro, Ed., Mack Publishing Company [1990]; Pharmaceutical Formulation Development of Peptides and Proteins, S. Frokjaer and L. Hovgaard, Eds., Taylor & Francis [2000]; and Handbook of Pharmaceutical Excipients, 3rd edition, A. Kibbe, Ed., Pharmaceutical Press [2000]). The RSV F polypeptides, or nucleic acid molecules, preferably are formulated and administered as a sterile solution although it may also be possible to utilize lyophilized preparations. Sterile solutions are prepared by sterile filtration or by other methods known per se in the art. The solutions are then lyophilized or filled into pharmaceutical dosage containers. The pH of the solution generally is in the range of pH 3.0 to 9.5, e.g. pH 5.0 to 7.5. The RSV F polypeptides typically are in a solution having a suitable pharmaceutically acceptable buffer, and the composition may also contain a salt. Optionally stabilizing agent may be present, such as albumin. In certain embodiments, detergent is added. In certain embodiments, the RSV F polypeptides may be formulated into an injectable preparation.

In certain embodiments, a composition according to the invention further comprises one or more adjuvants. Adjuvants are known in the art to further increase the immune response to an applied antigenic determinant. The terms "adjuvant" and "immune stimulant" are used interchangeably herein, and are defined as one or more substances that cause stimulation of the immune system. In this context, an adjuvant is used to enhance an immune response to the RSV F polypeptides of the invention. Examples of suitable adjuvants include aluminium salts such as aluminium hydroxide and/or aluminium phosphate; oil-emulsion compositions (or oil-in-water compositions), including squalene-water emulsions, such as MF59 (see e.g. WO 90/14837); saponin formulations, such as for example QS21 and Immunostimulating Complexes (ISCOMS) (see e.g. US 5,057,540; WO 90/03184, WO 96/11711, WO 2004/004762, WO 2005/002620);

bacterial or microbial derivatives, examples of which are monophosphoryl lipid A (MPL), 3-O-deacylated MPL (3dMPL), CpG-motif containing oligonucleotides, ADP-ribosylating bacterial toxins or mutants thereof, such as *E. coli* heat labile enterotoxin LT, cholera toxin CT, and the like; eukaryotic proteins (e.g. antibodies or fragments thereof (e.g. directed against the antigen
5 itself or CD1a, CD3, CD7, CD80) and ligands to receptors (e.g. CD40L, GMCSF, GCSF, etc), which stimulate immune response upon interaction with recipient cells. In certain embodiments the compositions of the invention comprise aluminium as an adjuvant, e.g. in the form of aluminium hydroxide, aluminium phosphate, aluminium potassium phosphate, or combinations thereof, in concentrations of 0.05 – 5 mg, e.g. from 0.075-1.0 mg, of aluminium content per
10 dose.

The pre-fusion RSV F polypeptides may also be administered in combination with or conjugated to nanoparticles, such as e.g. polymers, liposomes, virosomes, virus-like particles. The pre-fusion F polypeptides may be combined with, encapsidated in or conjugated to the nanoparticles with or without adjuvant. Encapsulation within liposomes is described, e.g. in US
15 4,235,877. Conjugation to macromolecules is disclosed, for example in US 4,372,945 or US 4,474,757.

In other embodiments, the compositions do not comprise adjuvants.

In certain embodiments, the invention provides methods for making a vaccine against respiratory syncytial virus (RSV), comprising providing a composition according to the
20 invention and formulating it into a pharmaceutically acceptable composition. The term "vaccine" refers to an agent or composition containing an active component effective to induce a certain degree of immunity in a subject against a certain pathogen or disease, which will result in at least a decrease (up to complete absence) of the severity, duration or other manifestation of symptoms

associated with infection by the pathogen or the disease. In the present invention, the vaccine comprises an effective amount of a pre-fusion RSV F polypeptide and/or a nucleic acid molecule encoding a pre-fusion RSV F polypeptide, and/or a vector comprising said nucleic acid molecule, which results in an immune response against the F protein of RSV. This provides a method of preventing serious lower respiratory tract disease leading to hospitalization and the decrease in frequency of complications such as pneumonia and bronchiolitis due to RSV infection and replication in a subject. The term “vaccine” according to the invention implies that it is a pharmaceutical composition, and thus typically includes a pharmaceutically acceptable diluent, carrier or excipient. It may or may not comprise further active ingredients. In certain embodiments it may be a combination vaccine that further comprises other components that induce an immune response, e.g. against other proteins of RSV and/or against other infectious agents. The administration of further active components may for instance be done by separate administration or by administering combination products of the vaccines of the invention and the further active components.

Compositions may be administered to a subject, e.g. a human subject. The total dose of the RSV F polypeptides in a composition for a single administration can for instance be about 0.01 µg to about 10 mg, e.g. 1 µg – 1 mg, e.g. 10 µg – 100 µg. Determining the recommended dose will be carried out by experimentation and is routine for those skilled in the art.

Administration of the compositions according to the invention can be performed using standard routes of administration. Non-limiting embodiments include parenteral administration, such as intradermal, intramuscular, subcutaneous, transcutaneous, or mucosal administration, e.g. intranasal, oral, and the like. In one embodiment a composition is administered by intramuscular

injection. The skilled person knows the various possibilities to administer a composition, e.g. a vaccine in order to induce an immune response to the antigen(s) in the vaccine.

A subject as used herein preferably is a mammal, for instance a rodent, e.g. a mouse, a cotton rat, or a non-human-primate, or a human. Preferably, the subject is a human subject.

5 The polypeptides, nucleic acid molecules, vectors, and/or compositions may also be administered, either as prime, or as boost, in a homologous or heterologous prime-boost regimen. If a boosting vaccination is performed, typically, such a boosting vaccination will be administered to the same subject at a time between one week and one year, preferably between two weeks and four months, after administering the composition to the subject for the first time (which is in such cases referred to as 'priming vaccination'). In certain embodiments, the administration comprises a prime and at least one booster administration.

10 In addition, the polypeptides of the invention may be used as diagnostic tool, for example to test the immune status of an individual by establishing whether there are antibodies in the serum of such individual capable of binding to the polypeptide of the invention. The invention thus also relates to an in vitro diagnostic method for detecting the presence of an RSV infection in a patient said method comprising the steps of a) contacting a biological sample obtained from said patient with a polypeptide according to the invention; and b) detecting the presence of antibody-polypeptide complexes.

20 The invention further provides a method for stabilizing the pre-fusion conformation of an RSV F polypeptide, comprising introducing at least one mutation in a RSV F1 and/or F2 domain, as compared to a wild-type RSV F1 and/or F2 domain, wherein the at least one mutation locks the alpha helix 4 from hinging or moving by a mutation in the triple helix in the RSV apex (alpha

helix 1, 4 and 5). In certain embodiments, the at least one mutation in alpha 4 is a mutation of the amino acid residue Leu into Ile at position 203.

Stabilized pre-fusion RSV F polypeptides obtainable and/or obtained by such method also form part of the invention, as well as uses thereof as described above.

5

Examples

EXAMPLE 1

In order to stabilize the labile apex of the pre-fusion conformation of RSV F, a Leu203Ile
10 substitution in alpha4 was introduced in a metastable RSV F variant with a stabilizing S215P mutation and a C-terminal fibrin motif.

Expression and purification of RSV F protein.

Recombinant proteins were expressed in 293 Freestyle cells (Life Technologies). The
15 cells were transiently transfected using 293Fectin (Life Technologies) according to the manufacturer's instructions and cultured in a shaking incubator at 37 °C and 10% CO₂. The culture supernatants containing F protein were harvested on the 5th day after transfection. Sterile-filtered supernatants were stored at 4 °C until use. The recombinant polypeptides were purified by a 2-step protocol applying a cation-exchange chromatography followed by size-exclusion
20 chromatography (Figure 1). For the ion-exchange step the culture supernatant was diluted with 2 volumes of 50 mM NaOAc pH 5.0 and passed over a 5 ml HiTrap Capto S (GE Healthcare) column at 5 ml per minute. Subsequently the column was washed with 10 column volumes (CV) of 20 mM NaOAc, 50 mM NaCl, 0.01% (v/v) tween20, pH 5 and eluted with 15% step elution of 50 mM NaOAc, 1 M NaCl, 0.01% (v/v) tween20, pH 5. The eluate was concentrated and the
25 protein was further purified on a Superdex200 column (GE Healthcare) using 40 mM Tris, 150

mM NaCl, 0.01% (v/v) tween20, and pH 7.4 as running buffer. The purified protein was analyzed on SDS-PAGE and Native PAGE (Figure 2). Proteins were visualized on the gel upon staining with Coomassie Brilliant Blue. Main bands on the SDS-PAGE are corresponding to F1 and F2 domains of RSV F protein in reduced samples; in non-reduces samples the main band corresponds to the size of F1+F2 domains linked together with disulfide bonds. On the Native Page electrophoretic mobility of the protein corresponds to one of the RSV F trimer. The pre-fusion conformation of the purified protein was confirmed by binding to CR9501 antibody (data not shown). The purified pre-fusion trimeric RSV F protein was stored at 4C until further analysis.

Stability studies.

The ability of the pre-fusion protein to spontaneously convert into post-fusion conformation was assessed in a storage stability assay. The crude cell culture supernatant samples were stored at 4 °C and concentration of the F protein in the samples was measured on Octet instrument by quantitative assay as described above. The measurement was done on the day of supernatant harvest (day1) and after storage for indicated period of time. CR9501 is a monoclonal antibody that only recognizes the pre-fusion F conformation (WO2012/006596) and was used to measure prefusion RSV F protein concentration.

Temperature stability of the purified proteins was determined by differential scanning fluorometry (DSF). The purified pre-fusion F protein was mixed with SYPRO orange fluorescent dye (Life Technologies S6650) in a 96-well optical qPCR plate. The optimal dye and protein concentration was determined experimentally (data not shown). All protein dilutions were performed in PBS, and a negative control sample containing the dye only was used as a reference

subtraction. The measurement was performed in a qPCR instrument (Applied Biosystems ViiA 7) using the following parameters: a temperature ramp from 25–95 °C with a rate of 0.015 °C per second. Data was collected continuously. The 1st derivative of the melting curves was plotted using GraphPad PRISM software (version 5.04). Melting temperatures were calculated at the minimum point of the derivative curve.

As shown in Figure 3 the metastable F variant that was only stabilized with the S215P substitution lost almost all binding to the pre-fusion-specific Mab CR9501 after storage for 5 days at 4 °C. In contrast, the additional L203I substitution increased the stability of this metastable RSV F variant dramatically. Total binding of CR9501 binding at day of harvest was higher and only a small drop in CR9501 binding was observed after storage of 15 days at 4 °C. An additional substitution of Leu 203 to Ile increases pre-fusion F stability storage stability compared to the metastable pre-fusion F protein that only contained the single S215P substitution. The additional L203I substitution also increased the heat stability (59.5 °C) compared to the variant that contained the N67I and S215P substitution (57.0 °C) according to the DSF experiments (Figure 4).

The constructs were tested for expression levels, storage stability and antibody binding with the antibody CR9501, specific for the pre-fusion conformation of RSV-F. The amino acid sequences of the heavy and light chain variable regions, and of the heavy and light chain CDRs of this antibody are given below. CR9501 comprises the binding regions of the antibodies referred to as 58C5 in WO2012/006596.

EXAMPLE 2

According to the present invention, it has been shown that the combination of the Leu203Ile substitution with other stabilizing mutations results in a very stable RSV F protein.

5 **Expression, purification and characterization of RSV F protein.**

Recombinant proteins were expressed and purified as described above. The purified protein was analyzed on SDS-PAGE (Figure 5). Proteins were pure with the only bands observed on gels corresponding to F1 and F2 domains of RSV F protein in reduced samples and to F1+F2 domains linked together in non-reduces samples. SEC-MALS analysis of the purified samples
10 (Figure 6) demonstrated that the only protein species present in the sample had molecular weight of ~170 kDa which corresponds to expected molecular weight of glycosylated RSV F trimer. The SEC-MALS was performed on an Agilent HPLC system using a TSK G3000SWXL column (Tosoh Bioscience). MALS measurements were performed using a MiniDAWN Treos in-line detector (Wyatt Technology). Protein concentration was monitored using a UV monitor at 280
15 nm and a refractive index detector at 660 nm (Optilab TrEX, Wyatt Technology). The detectors were plumbed in the order: UV, MALS, RI. SEC-MALS experiments employed MALS buffer (17,3 gr Na₂HPO₄ * 2 H₂O/L, 7.3 gr NaH₂PO₄ * H₂O/L, 2.9 gr NaCl/L, pH 7) and a flow rate of 1 ml/min. Data were analyzed using Astra software 6.1 (Wyatt Technology) using the refractive index detector and a refractive index increment (dn/dc) value of 0.141 ml/g. The
20 molecular weight is determined by using the peak maximum of the refractive index results, the total peak area is determined using the total peak area% of the UV-signal corrected for the extinction coefficient.

Stability studies.

Temperature stability of the purified proteins was determined by differential scanning fluorometry (DSF) as described in Example 1. As shown in Figure 4, when the L203I substitution was combined with S215P, D486N with or without N67I the heat stability of the proteins increase to ~67 and ~70°C respectively.

Table 1. Standard amino acids, abbreviations and properties

Amino Acid	3-Letter	1-Letter	Side chain polarity	Side chain charge (pH 7.4)
alanine	Ala	A	non-polar	Neutral
arginine	Arg	R	polar	Positive
asparagine	Asn	N	polar	Neutral
aspartic acid	Asp	D	polar	Negative
cysteine	Cys	C	non-polar	Neutral
glutamic acid	Glu	E	polar	Negative
glutamine	Gln	Q	polar	Neutral
glycine	Gly	G	non-polar	Neutral
histidine	His	H	polar	positive(10%) neutral(90%)
isoleucine	Ile	I	non-polar	Neutral
leucine	Leu	L	non-polar	Neutral
lysine	Lys	K	polar	Positive
methionine	Met	M	non-polar	Neutral
phenylalanine	Phe	F	non-polar	Neutral
proline	Pro	P	non-polar	Neutral
serine	Ser	S	polar	Neutral
threonine	Thr	T	polar	Neutral
tryptophan	Trp	W	non-polar	Neutral
tyrosine	Tyr	Y	polar	Neutral
valine	Val	V	non-polar	Neutral

Table 2. Amino acid sequences of antibodies CR9501 and CR9502

Ab	VH domain	VH CDR1	VH CDR2	VH CDR3
CR9501	Amino acids 1-125 of SEQ ID NO: 16	GASINSDNYWT (SEQ ID NO:1)	HISYTGNTYYTPSLKS (SEQ ID NO:2)	CGAYVLISNCGWFDS (SEQ ID NO:3)
CR9502	Amino acids 1-121 of SEQ ID NO:18	GFTFSGHTIA (SEQ ID NO:7)	WVSTNNGNTEYAQKI QG (SEQ ID NO:8)	EWLVMGGFAFDH (SEQ ID NO:9)

Ab	VL domain	VL CDR1	VL CDR2	VL CDR3
CR9501	Amino acids 1-107 of SEQ ID NO: 17	QASQDISTYLN (SEQ ID NO: 4)	GASNLET (SEQ ID NO:5)	QQYQYLPYT (SEQ ID NO:6)
CR9502	Amino acids 1-110 of SEQ ID NO: 19	GANNIGSQNVH (SEQ ID NO:10)	DDRDRPS (SEQ ID NO:11)	QVWDSSRDQAVI (SEQ ID NO:12)

The amino acid sequence of several of the pre-fusion RSV F constructs is given below. It

5 is noted that the amino acid numbering in the different constructs described herein is based on the wild-type sequence (SEQ ID NO: 13 with two modifications (K66E and I76V).

Sequences**RSV F protein A2 full length sequence (SEQ ID NO: 13)**

MELLILKANAITTILTAVTFCFASGQNITEEFYQSTCSAVSKGYLSALRTGWYTSVITIELS
5 NIKENKCNGTDAKVKLIKQELDKYKNAVTELQLLMQSTPATNNRARRELPRFMNYTLN
NAKKTNVTLSKKRKRRFLGFLLGVGSAIASGVAVSKVLHLEGEV NKIKSALLSTNKAVV
SLSNGVSVLT SKVLDLKNYIDKQLLPV NKQSCSISNIETVIEFQQKNNRLEITREFSVNA
GVTPPVSTYMLTNSELLSLINDMPITNDQKKLMSNNVQIVRQQSYSIMSIIKEEVLAYVV
QLPLYGVIDTPCWKLHTSPLCTTNTKEGSNICLTRTDRGWYCDNAGSVSFFPQAETCKV
10 QSNRVFCDTMNSLTLPSEVNLCNVDIFNPKYDCKIMTSKTDVSSSVITSLGAIVSCYGKT
KCTASNKNRGIKTF SNGCDYVSNKGVDTVSVGNTLYYV NKQEGKSLYVKGEPIINFYD
PLVFPSDEFDASISQVNEKINQSLAFIRKSDELLHNVNAVKSTTNIMITTHIIVIIVILLSLIAV
GLLLYCKARSTPVTLSKDQLSGINNIAFSN

15 RSV F protein B1 full length sequence (SEQ ID NO: 15)

MELLIHRLSAIFLTLAINALYLTSSQNITEEFYQSTCSAVSRGYFSALRTGWYTSVITIELS
NIKETKCNGTDTKV KLIKQELDKYKNAVTELQLLMQNTPAANNRARREAPQYMNYTIN
TTKNLNV SISKRRKR RFLGFLLGVGSAIASGIAVSKVLHLEGEV NKIKNALLSTNKAVVS
LSNGVSVLT SKVLDLKNYINNQLLPV NKQSCRISNIETVIEFQQKNSRLLEINREFSVNAG
20 VTTPLSTYMLTNSELLSLINDMPITNDQKKLMSSNVQIVRQQSYSIMSIIKEEVLAYVVQL
PIYGVIDTPCWKLHTSPLCTTNIKEGSNICLTRTDRGWYCDNAGSVSFFPQADTCKVQSN
RVFCDTMNSLTLPSEVSLCNTDIFNSKYDCKIMTSKTDISSSVITSLGAIVSCYGKTKCTA
SNKNRGIKTF SNGCDYVSNKGVDTVSVGNTLYYV NKLEGKNLYVKGEPIINYDPLVF
PSDEFDASISQVNEKINQSLAFIRRSDELLHNVNTGKSTTNIMITTHIIVIIVVLLSLIAIGLLL
25 YCKAKNTPVTLSKDQLSGINNIAFSK

SEQ ID NO: 14 (fibrin)

GYIPEAPRDGQAYVRKDG EWVLLSTFL

FA2, K66E, I76V, S215P (SEQ ID NO: 20)

MELLILKANAIITILTAVTFCFASGQNITEEFYQSTCSAVSKGYLSALRTGWYTSVITIELSNI
KENKCNGTDAKVKLIKQELDKYKNAVTELQLLMQSTPATNNRARRELPRFMNYTLNNAKKTNVT
LSKKRKRRLGFLGVSIAIASGVAVSKVLHLEGEVNIKSALLSTNKAVVSLNGVSVLTSTKV
5 LDLKNYIDKQLLPIVKNQSCSIPNIETVIEFQQKNNRLEITREFSVNAGVTTTPVSTYMLTNSE
LLSLINDMPITNDQKKLMSNNVQIVRQQSYSIMSIIEEVLAYVVQLPLYGVIDTPCWKLHTSP
LCTTNTKEGSNICLTRTRDRGWYCDNAGSVSFFPQAETCKVQSNRVFCDTMNSLTLPSEVNLCNV
DIFNPKYDCKIMTSKTDVSSSVITSLGAIVSCYGKTKCTASNKNRGI IKTFSNGCDYVSNKGVD
TVSVGNTLYYVKNQEGKSLYVKGEPIINFYDPLVFPSEFDASISQVNEKINQSLAFIRKSEDEL
10 LSAIGGYIPEAPRDGQAYVRKDGWVLLSTFL

FA2, K66E, I76V, L203I, S215P (SEQ ID NO: 21)

MELLILKANAIITILTAVTFCFASGQNITEEFYQSTCSAVSKGYLSALRTGWYTSVITIELSNI
KENKCNGTDAKVKLIKQELDKYKNAVTELQLLMQSTPATNNRARRELPRFMNYTLNNAKKTNVT
15 LSKKRKRRLGFLGVSIAIASGVAVSKVLHLEGEVNIKSALLSTNKAVVSLNGVSVLTSTKV
LDLKNYIDKQILPIVKNQSCSIPNIETVIEFQQKNNRLEITREFSVNAGVTTTPVSTYMLTNSE
LLSLINDMPITNDQKKLMSNNVQIVRQQSYSIMSIIEEVLAYVVQLPLYGVIDTPCWKLHTSP
LCTTNTKEGSNICLTRTRDRGWYCDNAGSVSFFPQAETCKVQSNRVFCDTMNSLTLPSEVNLCNV
DIFNPKYDCKIMTSKTDVSSSVITSLGAIVSCYGKTKCTASNKNRGI IKTFSNGCDYVSNKGVD
20 TVSVGNTLYYVKNQEGKSLYVKGEPIINFYDPLVFPSEFDASISQVNEKINQSLAFIRKSEDEL
LSAIGGYIPEAPRDGQAYVRKDGWVLLSTFL

FA2, K66E, I76V, L203I, S215P, D486N (SEQ ID NO: 23)

MELLILKANAIITILTAVTFCFASGQNITEEFYQSTCSAVSKGYLSALRTGWYTSVITIELSNI
25 KENKCNGTDAKVKLIKQELDKYKNAVTELQLLMQSTPATNNRARRELPRFMNYTLNNAKKTNVT
LSKKRKRRLGFLGVSIAIASGVAVSKVLHLEGEVNIKSALLSTNKAVVSLNGVSVLTSTKV
LDLKNYIDKQILPIVKNQSCSIPNIETVIEFQQKNNRLEITREFSVNAGVTTTPVSTYMLTNSE
LLSLINDMPITNDQKKLMSNNVQIVRQQSYSIMSIIEEVLAYVVQLPLYGVIDTPCWKLHTSP
LCTTNTKEGSNICLTRTRDRGWYCDNAGSVSFFPQAETCKVQSNRVFCDTMNSLTLPSEVNLCNV
30 DIFNPKYDCKIMTSKTDVSSSVITSLGAIVSCYGKTKCTASNKNRGI IKTFSNGCDYVSNKGVD
TVSVGNTLYYVKNQEGKSLYVKGEPIINFYDPLVFPSEFDASISQVNEKINQSLAFIRKSEDEL
LSAIGGYIPEAPRDGQAYVRKDGWVLLSTFL

FA2, K66E, N67I, I76V, L203I, S215P, D486N (SEQ ID NO: 24)

MELLILKANAITTILTAVTFCFASGQNITEEFYQSTCSAVSKGYLSALRTGWYTSVITIELSNI
KEIKCNGTDAKVKLIKQELDKYKNAVTELQLLMQSTPATNNRARRELPRFMNYTLNNAKKTNVT
LSKKRKRRLFLGFLLGVGSAIASGVAVSKVLHLEGEVNIKSALLSTNKAVVSLNGVSVLT
5 LDLKNYIDKQILPIVINKQSCSIPNIETVIEFQQKNNRLEITREFSVNAGVTTTPVSTYMLTNSE
LLSLINDMPITNDQKKLMSNNVQIVRQQSYSIMSIIEEVLAYVVQLPLYGVIDTPCWKLHTSP
LCTTNTKEGSNICLTRTRDRGWYCDNAGSVSFFPQAETCKVQSNRVFCDTMNSLTLPSEVNLCNV
DIFNPKYDCKIMTSKTDVSSSVITSLGAIVSCYGKTKCTASNKNRGIKTF SNGCDYVSNKGVD
TVSVGNTLYYVINKQEGKSLYVKGEPIINFYDPLVFP SNEFDASISQVNEKINQSLAFIRKSD
10 LSAIGGYIPEAPRDGQAYVRKDG EWVLLSTFL

RSV F protein CL57-v224 full length sequence (SEQ ID NO: 22)

MELPILKTNAITTILAAVTLCFASSQNITEEFYQSTCSAVSKGYLSALRTGWYTSVITIELS
NIKENKNGTDAKVKLIKQELDKYKNAVTELQLLMQSTPAANNRARRELPRFMNYTLN
15 NTKNNNVTL SKKRKRRLFLGFLLGVGSAIASGIAVSKVLHLEGEVNIKSALLSTNKAVV
SLSNGVSVLT SKVLDLKNYIDKQLLPIVINKQSCSISNIETVIEFQQKNNRLEITREFSVNA
GVTTTPVSTYMLTNSELLSLINDMPITNDQKKLMSNNVQIVRQQSYSIMSIIEEVLAYVV
QLPLYGVIDTPCWKLHTSPLCTTNTKEGSNICLTRTRDRGWYCDNAGSVSFFPQAETCKV
QSNRVFCDTMNSLTLPSEVNLCNIDIFNPKYDCKIMTSKTDVSSSVITSLGAIVSCYGKTK
20 CTASNKNRGIKTF SNGCDYVSNKGVDTVSVGNTLYYVINKQEGKSLYVKGEPIINFYDP
LVFPSDEFDASISQVNEKINQSLAFIRKSD ELLHNVNVGKSTTNIMITTHIIVILLLLIAV
GLFLYCKARSTPVTLSKDQLSGINNIAFSN

CR9501 heavy chain (SEQ ID NO: 16):

25 QVQLVQSGPGLVKPSQTLALTCNVSGASINS DNYYWTWIRQRPGGGLEWIGHISYTGNT
YYTPSLKSRLSMSLETSQSQFSLRLTSVTAADSAVYFCAACGAYVLISNCGWFDSWGQG
TQVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTSGVHTF
PAVLQSSGLYSLSSVVTVPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSC

CR9501 light chain (SEQ ID NO: 17):

EIVMTQSPSSLSASIGDRVTITCQASQDISTYLNWYQQKPGQAPRLLIYGASNLETGVPSR
FTGSGYGTDFSVTISSLQPEDIATYYCQQYQYLPYTFAPGTKVEIKRTVAAPSVFIFPPSDE
QLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSKDSYSTLSSTLTLS
5 KADYEKHKVYACEVTHQGLSSPVTKSFNRGEC

CR9502 heavy chain (SEQ ID NO: 18):

EVQLLQSGAELKKPGASVKISCKTSGFTFSGHTIAWVRQAPGQGLEWMGWVSTNNGNT
EYAQKIQGRVTMTMDTSTSTVYMELRSLTSDDTAVYFCAREWLMGGFAFDHWGQGT
10 LLTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTSGVHTFP
AVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKRVEPKSC

CR9502 light chain (SEQ ID NO: 19):

QSVLTQASSVSVAPGQTARITCGANNIGSQNVHWYQQKPGQAPVLVVYDDRDRPSGIP
15 DRFSGSNSGNTATLTISRVEAGDEADYYCQVWDSSRDQAVIFGGGTKLTVLGQPKAAPS
VTLFPPSSEELQANKATLVCLISDFYPGAVTVAWKADSSPVKAGVETTTPSKQSNNKYA
ASSYLSLTPEQWKSHRSYSCQVTHEGSTVEKTIAPTECS

Claims

1. A recombinant pre-fusion respiratory syncytial virus (RSV) Fusion (F) polypeptide,
wherein the polypeptide comprises at least two stabilizing mutations in the F1 and/or F2
5 domain as compared to the RSV F1 and/or F2 domain in a wild-type RSV F protein,
wherein at least one of the stabilizing mutations is a mutation of amino acid residue L on
position 203 into I.
2. The pre-fusion RSV F polypeptide according to claim 1, wherein the polypeptide further
10 comprises a mutation of amino acid residue S on position 215 to P.
3. The pre-fusion RSV F polypeptide according to claim 1, wherein the polypeptide
comprises at least one epitope that is specific to the pre-fusion conformation F protein,
wherein the at least one epitope is recognized by a pre-fusion specific monoclonal
15 antibody, comprising a heavy chain CDR1 region of SEQ ID NO: 1, a heavy chain CDR2
region of SEQ ID NO: 2, a heavy chain CDR3 region of SEQ ID NO: 3 and a light chain
CDR1 region of SEQ ID NO: 4, a light chain CDR2 region of SEQ ID NO: 5, and a light
chain CDR3 region of SEQ ID NO: 6 and/or a pre-fusion specific monoclonal antibody,
comprising a heavy chain CDR1 region of SEQ ID NO: 7, a heavy chain CDR2 region of
20 SEQ ID NO: 8, a heavy chain CDR3 region of SEQ ID NO: 9 and a light chain CDR1
region of SEQ ID NO: 10, a light chain CDR2 region of SEQ ID NO: 67, and a light
chain CDR3 region of SEQ ID NO: 11.

4. The pre-fusion RSV F polypeptide according to claim 1, wherein the polypeptide is trimeric.
5. The pre-fusion RSV F polypeptide according to claim 1, comprising a truncated F1 domain, wherein the polypeptide comprises a heterologous trimerization domain linked to the truncated F1 domain.
6. The pre-fusion RSV F polypeptide according to claim 5, wherein the heterologous trimerization domain comprises the amino acid sequence
GYIPEAPRDGQAYVRKDGEWVLLSTFL (SEQ ID NO: 14).
7. The pre-fusion RSV F polypeptide according to claim 5, wherein the trimerization domain is linked to the truncated F1 domain at amino acid residue 513 of the RSV F protein.
8. The pre-fusion RSV F polypeptide according to claim 1, wherein the at least one further mutation is selected from the group consisting of:
 - (a) a mutation of the amino acid residue S on position 46 into G;
 - (b) a mutation of the amino acid residue N/T on position 67 into I;
 - (c) a mutation of the amino acid residue L on position 83 into M;
 - (d) a mutation of the amino acid residue E on position 92 into D;
 - (e) a mutation of the amino acid residue G on position 184 into N;
 - (f) a mutation of the amino acid residue V on position 207 into I;
 - (g) a mutation of the amino acid residue D on position 486 into N; and
 - (h) a mutation of the amino acid residue E on position 487 into Q, N or I.

9. The pre-fusion RSV F polypeptide according to claim 1, wherein the F1 domain and/or the F2 domain are from an RSV A strain.

10. The pre-fusion RSV F polypeptide according to claim 1, wherein the F1 domain and/or the F2 domain are from an RSV B strain.

11. The pre-fusion RSV F polypeptide according to claim 1, wherein the polypeptide comprises an amino acid sequence selected from the group consisting of SEQ ID NO: 21, SEQ ID NO: 23 and SEQ ID NO: 24.

12. A composition comprising a pre-fusion RSV F polypeptide according to claim 1.

13. A pharmaceutical composition comprising the pre-fusion RSV F polypeptide according to claim 1, and a pharmaceutical carrier.