

**SORTASE-MEDIATED COUPLING OF IMMUNOGENIC POLYSACCHARIDE-PROTEIN CONJUGATES AND THEIR USE**

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**STATEMENT AS TO FEDERALLY FUNDED RESEARCH**

5 This invention was made with government support under grant number U19 AI09764 awarded by the National Institutes of Health. The government has certain rights in the invention.

**FIELD OF THE INVENTION**

The invention relates to immunogenic polysaccharide-protein conjugates, a novel sortase-mediated method of making immunogenic polysaccharide-protein conjugates, and methods of administering immunogenic polysaccharide-protein conjugates.

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**BACKGROUND OF THE INVENTION**

15 Many antigens, particularly those associated with a pathogen's capsule layer stimulate little or no immune response and complicate efforts to create effective immunogenic conjugates against those antigens. Capsules are surface components of microbes that are typically composed of polymers of organic compounds such as carbohydrates, amino acids, or alcohols. Capsules are quite diverse chemically. The monomeric units that make up capsules (e.g., carbohydrates) can be linked together in various molecular configurations and can be further substituted with phosphate, nitrogen, sulfate, and other chemical modifications. These chemical variations allow capsules to present numerous antigenic targets on the microbial surface, thus allowing escape from the host immune response directed at these targets. Capsules can also be virulence factors which prevent microbes from being phagocytosed and killed by host macrophages and polymorphonuclear leukocytes. Antibodies against capsules provide a potent defense against encapsulated organisms by fixing complement to the microbial surface, which can result in their lysis or their opsonization, uptake, and killing by phagocytic host immune cells. The most potent antibodies against capsules are IgG antibodies. Capsules that fail to induce significant levels of IgG are called T-independent antigens. Covalent coupling of a protein to capsules renders them "T-dependent" and such antigens can elicit an IgG response.

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30 There is a need for safe, synthetically accessible, cost-effective immunogenic conjugates directed to capsules and other T-independent antigens that do not evoke strong immune responses or IgG antibodies. Such immunogenic conjugates are needed to protect against various infectious diseases such as infection by anthrax, pneumococcus, influenzae Type B, meningococcus, and streptococcus.

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**SUMMARY OF THE INVENTION**

35 The present invention relates to immunogenic compositions containing a polysaccharide antigen conjugated with a carrier protein in a complex, methods of making such immunogenic compositions, and methods of administering such immunogenic compositions.

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In a first aspect, the invention features an immunogenic composition including a polysaccharide-sortase conjugate, wherein the polysaccharide is an antigen and the sortase is a carrier protein, and wherein the sortase is covalently linked to the polysaccharide antigen through a linker containing a sortase recognition sequence.

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In a second aspect, the invention features an immunogenic composition including a polysaccharide-protein conjugate, the conjugate including a polysaccharide antigen and a carrier protein, wherein the polysaccharide antigen is covalently linked to the carrier protein through a linker containing a sortase recognition sequence and a polyglycine motif present at the N-terminus of the carrier protein.

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In some embodiments, the immunogenic composition includes a sortase selected from sortase A, sortase B, sortase C, and sortase D. The immunogenic composition may include a sortase A, or a fragment thereof. The immunogenic composition may include sortase A having the amino acid sequence of SEQ ID NO:

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1. The immunogenic composition may include a sortase having an amino acid sequence

that has at least 90% identity to the amino acid sequence of SEQ ID NO: 1. The immunogenic composition

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may include a sortase having an amino acid sequence that has at least 95% identity to the amino acid sequence of SEQ ID NO: 1. The immunogenic composition may include a sortase having an amino acid sequence that has at least 99% identity to the amino acid sequence of SEQ ID NO: 1. The immunogenic composition may include a sortase B, or a fragment thereof. The immunogenic

composition may include a sortase C, or a fragment thereof. The immunogenic composition may include a sortase D, or a fragment thereof.

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In additional embodiments, the immunogenic composition may include a sortase including at least one mutation. The immunogenic composition may include a sortase that includes a substitution.

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The immunogenic composition may include the sortase recognition sequence having the formula  $X_1PX_2X_3$

$X_4$ , where  $X_1$ - $X_4$  are any amino acid. The immunogenic composition may further include the sortase recognition sequence having the formula  $X_1PX_2X_3G$  for a sortase A substrate, where  $X_1$  is Leu, Ile, Val or Met,  $x_2$  is any amino acid, and  $X_3$  is Ser, Thr or Ala. The immunogenic composition may include the sortase recognition sequence  $LPX_1TG$  for a sortase A substrate, where  $X_1$  is any amino acid. The

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immunogenic composition may include the sortase recognition sequence  $NPX_1TX_2$  for a sortase B substrate,

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where  $X_1$  is Lys or Gln and  $X_2$  is Asn, Asp, or Gly. The immunogenic composition may include the sortase recognition sequence  $LPX_1TX_2$  for a sortase C substrate, where  $X_1$  and  $X_2$  are any amino acid. The immunogenic composition may include the sortase recognition sequence  $LPX_1TA$  for a sortase D substrate, where  $X_1$  is any amino acid. The immunogenic composition may include the sortase

recognition sequence,  $LAX_1TG$  for a sortase D substrate, where  $X_1$  is any amino acid.

In other embodiments, the invention features an immunogenic composition where the polyglycine motif includes an amino acid sequence selected from GG, GGG, GGGG, and GGGGG. The invention further includes an immunogenic composition where the polyglycine motif includes the amino acid

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sequence GGGGG.

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In certain embodiments, the sortase recognition sequence is linked to the polysaccharide through



where Z<sup>1</sup> is a bond to an oxygen atom in the polysaccharide,

Z<sup>2</sup> is a bond to a carbonyl group in the sortase recognition sequence,

Z<sup>3</sup> is O or NH,

each of n and m is 0 or 1, and

L, when present, is C<sub>2-6</sub> alkanediyl or C<sub>6-10</sub> arenediyl.

In another embodiment, the immunogenic composition of the invention includes carrier protein molecules that are selected from diphtheria toxin, diphtheria toxoid, tetanus toxin, tetanus toxoid, *Pseudomonas aeruginosa* exotoxin A, cholera toxin B subunit, tetanus toxin fragment C, bacterial

5 flagellin, pneumolysin, an outer membrane protein of *Neisseria meningitidis*, *Pseudomonas aeruginosa*

Hcp1 protein, *Escherichia coli* heat labile enterotoxin, shiga-like toxin, human LTB protein, pneumolysin, listeriolysin O, a protein extract from whole bacterial cells, the dominant negative mutant (DNI) of the

10 protective antigen of *Bacillus anthracis*, and *Escherichia coli* beta-galactosidase. The invention also features an immunogenic composition where the whole bacterial cells are *Pseudomonas aeruginosa* or

10 *Streptococcal* cells. The invention includes an immunogenic composition where the bacterial flagellin is the *Vibrio cholerae* flagellin protein. The invention includes an immunogenic composition where the shiga-like toxin is the *Shigella* StB2 protein.

In additional embodiments, the immunogenic composition includes an antigen of interest where

15 the antigen of interest is a polysaccharide, a polyalcohol, or a poly amino acid. The polysaccharide of the immunogenic composition may include at least 18 residues. The polysaccharide of the immunogenic

composition may include a *Streptococcus pneumoniae* polysaccharide, *Francisella tularensis* polysaccharide, *Bacillus anthracis* polysaccharide, *Haemophilus influenzae* polysaccharide, *Salmonella typhi* polysaccharide, *Salmonella* species polysaccharide, *Shigella* polysaccharide, or *Neisseria*

20 *meningitidis* polysaccharide. The *Streptococcus pneumoniae* polysaccharide of the immunogenic composition may be a capsular type 1, 2, 3, 4, 5, 6A, 6B, 7A, 7B, 7C, 7F, 8, 9A, 9L, 9N, 9V, 10A, 10B, 10F, 11A, 11B, 11C, 11D, 11F, 12A, 12B, 12F, 13, 14, 15A, 15B, 15C, 15F, 16A, 16F, 17A, 17F, 18A, 18B, 18C, 18F, 19A, 19B, 19C, 19F, 20, 21, 22F, 23B, 23F, 24A, 24B, 24F, 25A, 25F, 27, 28A, 28F, 29,

25 31, 32A, 32F, 33A, 33B, 33D, 33F, 34, 35A, 35B, 35F, 36, 37, 38, 39, 40, 41A, 41F, 42, 43, 44, 45, 46, 47A, 47F, or 48. The immunogenic composition of the invention may further include a *Francisella tularensis* polysaccharide that is an O antigen.

In further embodiments, the antigen of interest of the immunogenic composition is a microbial

capsular polymer. The microbial capsular polymer of the immunogenic composition may include a poly-

30 gamma-D-glutamic acid from *Bacillus anthracis*. The antigen of interest of the immunogenic composition may also include an organic polymer consisting of monomers having at least three atoms where each of the atoms is independently selected from carbon, oxygen, hydrogen, phosphate, nitrogen, and sulfate. The antigen of interest may include an organic polymer that is obtained from a microbe and/or does not occur in nature.

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The immunogenic composition may further include, e.g., a second antigen of interest or a third antigen of interest. The immunogenic composition may include an antigen of interest including whole cell pathogens where the whole cell pathogens include heat inactivated whole cell pathogens; chemically inactivated whole cell pathogens; and/or *Pseudomonas aeruginosa* or *Streptococcal* cells, wherein the

5 *Streptococcal* cells include *Streptococcus pneumoniae*. The immunogenic composition may further include whole cell pathogens from *Streptococcus pneumoniae* type 1, 2, 3, 4, 5, 6A, 6B, 7A, 7B, 7C, 7F, 8, 9A, 9L, 9N, 9V, 10A, 10B, 10F, 11A, 11B, 11C, 11D, 11F, 12A, 12B, 12F, 13, 14, 15A, 15B, 15C, 15F, 16A, 16F, 17A, 17F, 18A, 18B, 18C, 18F, 19A, 19B, 19C, 19F, 20, 21, 22F, 23B, 23F, 24A, 24B, 24F, 25A, 25F, 27, 28A, 28F, 29, 31, 32A, 32F, 33A, 33B, 33D, 33F, 34, 35A, 35B, 35F, 36, 37, 38, 39, 40,

10 41A, 41 F, 42, 43, 44, 45, 46, 47A, 47F, or 48. The antigen of interest of the immunogenic composition may include at least one whole cell pathogen selected from the group consisting of *Streptococcus pneumoniae* type 1, 2, 3, 4, 5, 6A, 6B, 7A, 7B, 7C, 7F, 8, 9A, 9L, 9N, 9V, 10A, 10B, 10F, 11A, 11 B, 11C, 11D, 11F, 12A, 12B, 12F, 13, 14, 15A, 15B, 15C, 15F, 16A, 16F, 17A, 17F, 18A, 18B, 18C, 18F, 19A, 19B, 19C, 19F, 20, 21, 22F, 23B, 23F, 24A, 24B, 24F, 25A, 25F, 27, 28A, 28F, 29, 31, 32A, 32F, 33A,

15 33B, 33D, 33F, 34, 35A, 35B, 35F, 36, 37, 38, 39, 40, 41A, 41F, 42, 43, 44, 45, 46, 47A, 47F, and 48. The antigen of interest may also include two or more whole cell pathogens selected from the group consisting of *Streptococcus pneumoniae* type 1, 2, 3, 4, 5, 6A, 6B, 7A, 7B, 7C, 7F, 8, 9A, 9L, 9N, 9V, 10A, 10B, 10F, 11A, 11B, 11C, 11D, 11F, 12A, 12B, 12F, 13, 14, 15A, 15B, 15C, 15F, 16A, 16F, 17A, 17F, 18A, 18B, 18C, 18F, 19A, 19B, 19C, 19F, 20, 21, 22F, 23B, 23F, 24A, 24B, 24F, 25A, 25F, 27, 28A, 28F,

20 29, 31, 32A, 32F, 33A, 33B, 33D, 33F, 34, 35A, 35B, 35F, 36, 37, 38, 39, 40, 41A, 41F, 42, 43, 44, 45, 46, 47A, 47F, and 48.

The invention features an immunogenic composition that, when administered to a mammal, elicits a T-cell dependent immune response in the mammal. In the immunogenic composition of the invention,

25 the molar ratio of the antigen to the carrier protein molecules may be 1 to 1.

The invention further features a pharmaceutical composition in unit dosage form including (i) the immunogenic composition of the invention and (ii) a pharmaceutically acceptable excipient. [In some embodiments the pharmaceutical composition does not comprise an adjuvant.](#)

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In another aspect, the invention features a method of making an immunogenic composition including a polysaccharide-protein conjugate, the method includes mixing a polysaccharide antigen including a sortase recognition sequence and a sortase where the mixing results in formation of a thioester bond between the polysaccharide antigen and the sortase, yielding the polysaccharide-protein

35 conjugate. The method of making an immunogenic composition may further include mixing the polysaccharide-protein conjugate and a carrier protein including a polyglycine motif at its N-terminus where the mixing results in formation of a peptide bond between a terminal carboxyl group of a sortase recognition sequence attached to the polysaccharide antigen and a terminal amino group of the polyglycine motif of the carrier protein. The method of making an immunogenic composition may include

40 the polysaccharide antigen that is a whole cell pathogen.

In certain embodiments, the method further includes lysing the whole cell pathogen to produce a polysaccharide-protein conjugate, in which the polysaccharide antigen is not a whole cell pathogen. In particular embodiments, the immunogenic composition is purified (e.g., to separate the immunogenic composition from unreacted starting materials, reaction byproducts, and/or cellular debris). In further  
5 embodiments, the method further includes preparing the polysaccharide antigen containing the sortase recognition sequence by mixing a polysaccharide cyanate with a hydrazine-activated sortase recognition sequence, thereby effecting an addition reaction of a hydrazine moiety in the hydrazine-activated sortase recognition sequence to a cyanate group in the polysaccharide cyanate.

In additional embodiments, the invention features the use of the immunogenic composition of the invention to generate an immune response in a subject including administering the pharmaceutical composition of the invention to a subject where the immunogenic composition elicits a T-cell dependent immune response in the subject. The invention also features a method of generating an immune response in a subject including administering the pharmaceutical composition of the invention to a subject where the immunogenic composition elicits a T-cell dependent immune response in the subject. The subject may be an infant, a child, or an adolescent. In certain embodiments, the pharmaceutical composition is administered to the subject parenterally. In other embodiments, the pharmaceutical composition is administered to the subject orally.

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**DEFINITIONS**

By "administering" as used herein in conjunction with an immunogenic conjugate, is meant providing to a subject an immunogenic conjugate in a dose sufficient to induce an immune response in the subject, where the immune response results in the production of antibodies that specifically bind an

5 antigen contained in the immunogenic conjugate. Administering desirably includes parenteral administration (for instance, by subcutaneous, intramuscular, intravenous, or intradermal injection). While administering by a means that physically penetrates the dermal layer is desirable (e.g., a needle, airgun, or abrasion), the immunogenic conjugates of the invention can also be administered by transdermal absorption. Desirably, administration involves inclusion of the appropriate immune adjuvants.

10 Administering also includes enterally (for instance, by oral administration) by ingestion of an immunogenic conjugate in the form of e.g., a liquid, powder, capsule, or tablet. Administering may involve a single administration of an immunogenic conjugate or administering an immunogenic conjugate in multiple doses. Desirably, a second administration is designed to boost production of antibodies in a subject to reduce the likelihood of infection by an infectious agent. The frequency and quantity of the dosage of

15 immunogenic conjugate depends on the specific activity of the immunogenic conjugate and can be readily determined by routine experimentation.

By "alkanediyyl" is meant a divalent, saturated hydrocarbon group having a total of 2 to 6 carbon atoms. An alkanediyyl may be linear or branched. Non-limiting examples of the alkanediyyl groups are: 20 ethane-1,2-diyyl; propane-1,3-diyyl; propane-1,2-diyyl; 2-methyl-propane-1,3-diyyl; butane-1,2-diyyl; butane-1,3-diyyl; and butane-1,4-diyyl.

By "arenediyyl" is meant a divalent, cyclic, aromatic group having a total of 6 to 10 carbon atoms. Non-limiting examples of the arenediyyl groups are phenylene and naphthylene.

25 By "amino acid" is meant a residue in a polypeptide sequence that can be naturally occurring or synthetic. A naturally occurring amino acid is one encoded by the genetic code. A synthetic amino acid is one that is analogous in chemical structure to a naturally occurring amino acid; or one that has a different chemical structure from a naturally occurring amino acid yet functions similarly to a naturally occurring amino acid. Amino acids may be referred to herein by their single or three letter abbreviations.

30 The single letter abbreviation for a particular amino acid, its corresponding amino acid, and three letter abbreviation are as follows: A, alanine (Ala); C, cysteine (Cys); D, aspartic acid (Asp); E, glutamic acid (Glu); F, phenylalanine (Phe); G, glycine (Gly); H, histidine (His); I, isoleucine (Ile); K, lysine (Lys); L, leucine (Leu); M, methionine (Met); N, asparagine (Asn); P, proline (Pro); Q, glutamine (Gln); R, arginine 35 (Arg); S, serine (Ser); T, threonine (Thr); V, valine (Val); W, tryptophan (Trp); and Y, tyrosine (Tyr).

By "antigen" as used herein is meant any molecule or combination of molecules that is specifically bound by an antibody or an antibody fragment.

40 By "boost the production of antibodies" is meant the activation of memory B-cells that occurs during a second exposure to an antigen, called a "booster response," and is indicative of a long lived "secondary" memory immune response, resulting in the long lived production of antibodies.

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By "carrier protein" is meant a protein used in an immunogenic composition that invokes an immune response to itself and/or to an antigenic polysaccharide covalently linked with a carrier protein. Desirably, the carrier protein contains an epitope recognized by a T-cell. Also encompassed by the

5 definition of a carrier protein are enzymes of the sortase family of proteins. Desirably, a carrier protein includes multi-antigenic peptides (MAPs), which are branched peptides and include lysine. Exemplary desirable carrier proteins include toxins and toxoids (chemical or genetic), which may be mutant. Desirably, a carrier protein is diphtheria toxin or a mutant thereof, diphtheria toxoid, tetanus toxin or a mutant thereof, tetanus toxoid, *Pseudomonas aeruginosa* exotoxin A or a mutant thereof, cholera toxin B

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10 subunit, tetanus toxin fragment C, bacterial flagellin, pneumolysin, listeriolysin O (and related molecules), an outer membrane protein of *Neisseria meningitidis*, *Pseudomonas aeruginosa* Hcp1 protein, *Escherichia coli* heat labile enterotoxin, shiga-like toxin, human LTB protein, a protein extract from whole bacterial cells, the dominant negative mutant (DNI) of the protective antigen of *Bacillus anthracis*, or *Escherichia coli* beta-galactosidase, or any other protein that can be conjugated by a peptide linker. A

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15 carrier protein can also include one or more affinity purification tags. Affinity purification tags are known in the art: non-limiting examples of the purification tags are poly-His tags (e.g., oligohistidines having from 5 to 10 His repeating units or from 6 to 9 repeating units), poly-Arq tag, FLAG-tag, calmodulin-tag, S-tag, SBP-tag, TC tag, Strep-tag, VSV-tag (vesicular stomatitis virus tag), Xpress tag, Isopeptag, Halo-tag, GFP-tag, biotin carboxyl carrier protein, chitin binding protein (CBP), maltose binding protein (MBP),

20 glutathione-S-transferase (GST), V5-tag, Myc-tag, and HA-tag. The affinity tags have been described in *Terpe Appl. Microbiol. Biotechnol.*, 60:523-533, 2003; Schmidt et al., *Nat. Protocol.*, 2:1528-1535, 2007; the disclosure of which is incorporated herein by reference.

By "conjugated" or "conjugation" is meant an association of two entities, for example, of two  
25 molecules such as a polysaccharide and a protein. The association can be, for example, via an indirect (e.g., via a peptide linker) covalent linker connecting both molecules. Exemplary desirable conjugations include a polysaccharide and a carrier protein conjugated to each other to form a polysaccharide-protein fusion, where the polysaccharide and carrier protein are conjugated via a linker, e.g., an amino acid sequence connecting a polysaccharide side chain to an amino acid residue of the carrier protein.

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30 Desirably, conjugation of a polysaccharide to a carrier protein is achieved by transpeptidation, where the carrier protein is a sortase enzyme. Desirably, conjugation of a polysaccharide to a carrier protein is achieved by transamidation, where the carrier protein replaces a sortase covalently linked to a polysaccharide to form a new polysaccharide-carrier protein conjugate. A carrier protein may be covalently linked to a polysaccharide through a linker containing  $Z^1-C(Z^2)-N(H)-N(H)-(-C(O)-(L-C(O)))n-$

35  $N(H)-N(H)-m-Z^2$ , where  $Z^1$  is a bond to an oxygen atom in the polysaccharide or a the whole cell pathogen,  $Z^2$  is a bond to a carbonyl group in the sortase recognition sequence or in the a carrier protein, e.g., containing sortase (e.g., a C-terminal carbonyl, aspartic acid side chain carbonyl, or glutamic acid side chain carbonyl),  $Z^3$  is O or NH, each of n and m is 0 or 1, and L, when present, is  $\alpha$ -6 alkanediyl or O6-10 arenediyl.

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By "covalently linked" is meant the formation of a covalent bond between two molecules, macromolecules, or combination of molecules, e.g., between a polysaccharide and a carrier protein.

5 By "DNI" is meant the dominant negative mutant (DNI) protein, which is a mutated form of protective antigen (PA) of *B. anthracis*, as described by Benson et al. (*Biochemistry* 37:3941-3948, 1998).

By "electrophilic source of cyanide" is meant a compound that upon reaction with a hydroxyl of an alcohol produces a cyanate group. Non-limiting examples of the electrophilic sources of cyanide include 1-cyano-4-dimethylaminopyridinium tetrafluoroborate (CDAP) or cyanogen bromide.

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By "hydrazine-activated sortase recognition sequence" is meant a sortase recognition sequence that is modified to include H2N-NH- group.

15 By "hydrazine source agent" is meant a compound capable of reacting with a carrier protein to produce a hydrazine-activated sortase recognition sequence. In some embodiments, the formula of a hydrazine source agent is  $H_2N-N(H)-(-C(O)-(L-C(O)))_n-N(H)-N(H)-m-H$ , in which each of  $n$  and  $m$  is 0 or 1, and  $L$  is  $o$ - $o$  alkanediyl or  $C$ 6- $10$  arenediyl. Non-limiting examples of hydrazine source agents are hydrazine and dicarboxylic acid dihydrazides (e.g., succinic acid dihydrazide or adipic acid dihydrazide).

20 By "infection" is meant the invasion of a subject by a microbe, e.g., a bacterium, fungus, parasite, or virus. The infection may include, for example, the excessive multiplication of microbes that are normally present in or on the body of a subject or multiplication of microbes that are not normally present in or on a subject. A subject is suffering from a microbial infection when an excessive amount of a microbial population is present in or on the subject's body or when the presence of a microbial

25 population(s) is damaging the cells or causing pathological symptoms to a tissue of the subject.

By "infectious agent" is meant a microbe, such as a bacterium, fungus, parasite, or virus that is capable of causing an infection in a subject.

30 By "immunogenic" is meant a compound that induces an immune response in a subject. Desirably, the immune response is a T-cell dependent immune response that involves the production of IgG antibodies.

35 By "microbial capsular polymer" is meant a polymer present in or on the capsule coating of a microbe. Desirably, a microbial capsular polymer is an organic polymer such as a polysaccharide, phosphopolysaccharide, polysaccharide with an amino sugar with a N-acetyl substitution, polysaccharide containing a sulfonated sugar, another sulfate-modified sugar, or phosphate-modified sugar, polyalcohol, poly amino acid, teichoic acid, and an O side chain of a lipopolysaccharide.

40 By "monomer" is meant a molecular structure capable of forming two or more bonds with like monomers, often yielding a chain or a series of branched, connected chains of repeating monomer

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substructures, when part of a "polymer."

By "organic polymer" is meant a polymer composed of covalently linked monomers each having three or more of the following atoms: carbon, oxygen, hydrogen, phosphate, nitrogen, and sulfate.

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5 Desirably, an organic polymer is a polysaccharide, phosphopolysaccharide, polysaccharide with an amino sugar with a N-acetyl substitution, polysaccharide containing a sulfonated sugar, another sulfate-modified sugar, or phosphate-modified sugar, sugar, polyalcohol, polyamino acid, teichoic acid, and an O side chain of lipopolysaccharide.

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10 By "polyalcohol" is meant a hydrogenated form of a carbohydrate where a carbonyl group has been reduced to a primary or secondary hydroxyl group. Exemplary polyalcohols are a polyalkylene oxide (PAO), such as a polyalkylene glycols (PAG), including polymethylene glycols, polyethylene glycols (PEG), methoxypolyethylene glycols (MPEG) and polypropylene glycols; poly-vinyl alcohol (PVA); polyethylene-co-maleic acid anhydride; polystyrene-co-maleic acid anhydride; dextrans including

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15 carboxymethyl-dextrans; celluloses, including methylcellulose, carboxymethylcellulose, ethylcellulose, hydroxyethylcellulose carboxyethylcellulose, and hydroxypropylcellulose; hydrolysates of chitosan; starches such as hydroxyethyl-starches and hydroxy propyl-starches; glycogen; agaroses and derivates thereof; guar gum; pullulan; insulin; xanthan gum; carrageenan; pectin; alginic acid hydrolysates; sorbitol; an alcohol of glucose, mannose, galactose, arabinose, gulose, xylose, threose, sorbose, fructose,

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20 glycerol, maltose cellobiose, sucrose, amylose, amylopectin; or mono propylene glycol (MPG).

By "polyglycine" is meant a (Gly)<sub>n</sub> sequence. Desirably n is between 2 and 20, or more desirably between 2 and 5, and even more desirably 5 glycine residues.

25 By "polysaccharide antigen" is meant a polymer of saccharides (sugars) derived from capsules of encapsulated bacterial pathogens such as *Streptococcus pneumoniae*, *Francisella tularensis*, *Bacillus anthracis*, *Haemophilus influenzae*, *Salmonella typhi*, *Salmonella* species, *Shigella*, or *Neisseria meningitidis* that is specifically bound by an antibody or an antibody fragment.

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30 By "sortase" is meant a protein having a catalytic domain with activity capable of i) selectively cleaving a backbone amide bond of a polypeptide (peptidase activity) at a "sortase recognition sequence," and ii) selectively catalyzing the formation of an amide bond between the terminal carboxyl group created by the cleavage and the free primary amino (R-CH<sub>2</sub>-NH<sub>2</sub>-R') group of a glycine, (transamidase activity). Sortases may be derived from enzymes expressed on the surface of Gram-

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35 positive bacteria which cleave cell surface proteins and link them to cell wall proteoglycans. Sortases may desirably be derived from one of four families of sortase enzymes including sortase A, sortase B, sortase C, and sortase D.

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40 By "sortase ligation sequence" is meant an amino acid sequence that is capable of being selectively ligated to a second amino acid sequence by a sortase. A sortase ligation sequence can be either a sortase recognition sequence or a polyglycine sequence.

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By "sortase recognition sequence" is meant the consensus sequence for a sortase enzyme substrate. Desirably, the consensus sequence is  $X_1PX_2X_3G$  for a sortase A substrate, where  $X_1$  is Leu, Ile, Val or Met, P is Pro,  $X_2$  is any amino acid,  $X_3$  is Ser, Thr or Ala, and G is Gly. Desirably, the sortase recognition sequence for sortase A is  $LPX_1TG$ . Desirably the consensus sequence is  $NPX_1TX_2$  for a  
 5 sortase B substrate, where N is Asn, P is Pro,  $X_1$  is Lys or Gln, T is Thr, and  $X_2$  is Asn, Asp, or Gly. Desirably, the sortase recognition sequence for sortase C is  $LPX_1TX_2$ , where L is Leu, P is Pro,  $X_1$  and  $X_2$  are any amino acid residue, and T is Thr. Desirably the consensus sequences for sortase D are  $LPX_1TA$  or  $LAX_1TG$ , where L is Leu, P is Pro,  $X_1$  is any amino acid, T is Thr, A is Ala, and G is Gly. In the immunogenic compositions containing a polysaccharide covalently linked to a carrier protein, the sortase  
 10 recognition sequence is a fragment resulting from the reaction of the sortase recognition sequence with a sortase.

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By "subject" is meant an animal that can be infected by a microbe. Desirably, a subject is a mammal such as a human, monkey, dog, cat, mouse, rat, cow, sheep, goat, or horse. In a desirable  
 15 embodiment, the subject is a human, such as a human child. Desirably, the subject is a human infant, toddler, pre-pubescent child, pubescent child, young adult, or adult under the age of 55 years old.

By "T-cell independent antigen" is meant an antigen which results in the generation of antibodies without the cooperation of T lymphocytes. The T-cell independent antigen desirably directly stimulates B  
 20 lymphocytes without the cooperation of T lymphocytes. Exemplary desirable T-cell independent antigens include capsular antigen poly-gamma-D-glutamic acid (PGA), alginic acid (algenate), dextran, polysaccharides (PS), poly amino acids, polyalcohols, and nucleic acids.

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The term "percent (%) identity" with respect to a reference polypeptide sequence is defined as the  
 25 percentage of amino acid residues in a candidate sequence that are identical with the amino acid residues in the reference polypeptide sequence, after aligning the sequences and introducing gaps, if necessary, to achieve the maximum percent sequence identity, and not considering any conservative substitutions as part of the sequence identity. Alignment for purposes of determining percent identity to a polypeptide sequence can be achieved in various ways that are within the skill in the art, for instance,  
 30 using publicly available computer software such as BLAST, BLAST-2, ALIGN or Megalign (DNASTAR) software. Those skilled in the art can determine appropriate parameters for aligning sequences, including any algorithms needed to achieve maximal alignment over the full length of the sequences being compared. For example, for a reference polypeptide of amino acid sequence A, when compared to the derivative polypeptide of amino acid sequence B, the percent identity to an amino acid sequence is

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35 calculated as:

$$100 \text{ times the fraction } X/Y,$$

where X is the number of amino acid sequence residues scored as identical matches between A and B,  
 and where Y is the total number of amino acid residues in the polypeptide sequence of B.

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40 Advantages

Compared to existing immunogenic conjugate technologies, the immunogenic conjugate  
 compositions of the present invention are simple to make, less expensive, and more adaptive to different

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antigens of interest and carrier proteins than existing conjugate technologies.

The immunogenic conjugates of the present invention do not require that each combination of carrier protein and the antigen intended to evoke an immune response be conjugated by a tailored ligation process unique to their respective chemical properties. Polysaccharide (PS)-protein immunogenic conjugates have been prohibitively expensive to produce and sell in the developing world, and conventional immunogenic conjugates are difficult to produce cheaply because of the highly specialized chemistry required for each antigen-protein conjugate. Thus, the present invention simplifies the method of making these conjugates and reduces the cost of their preparation compared to current immunogenic conjugate technology.

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The immunogenic conjugates of the present invention also address a need for immunogenic conjugates that can safely induce immunity against previously intractable antigens. Immunogenic conjugates containing TLR (Toll-like receptor) ligands have been shown to evoke immune responses for otherwise intractable antigens, but they tend to be unsafe because TLR ligands are often proinflammatory, toxic in even small doses, reactogenic, and likely to cause adverse symptoms compared to immunogenic conjugates of the invention.

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Other features and advantages of the invention will be apparent from the following detailed description, the drawings, and the claims.

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**BRIEF DESCRIPTION OF THE DRAWINGS**

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FIG. 1 is a schematic of a conjugation reaction between a protein (Protein 1) and a peptidoglycan (Polysaccharide 1) catalyzed by a sortase in *Staphylococcus aureus*. In this model, sortase recognizes a C-terminus peptide signal ("LPXTGXX") on a protein and forms an intermediate conjugate with a protein before recognizing an N-terminus peptide signal ("GGG") on a peptidoglycan. In the final step, sortase covalently links a protein to a peptidoglycan to form a final conjugate.

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FIG. 2 is a schematic of a conjugation reaction between a polysaccharide (polysaccharide 2) and a protein (protein 2) catalyzed by a sortase. In this model, sortase recognizes a C-terminus peptide signal ("LPXTGXX") on a PS and forms an intermediate PS-sortase conjugate (conjugate 1). In the presence of a protein containing an N-terminus recognition sequence ("GGG"), sortase covalently links a protein to a PS to form a final PS-protein conjugate (conjugate 2).

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**DETAILED DESCRIPTION**

The invention features novel immunogenic compositions and methods of making and administering such compositions to provide immunity against T-cell independent antigens or antigens which normally invoke weak immune responses, such as, e.g., polysaccharides (PS), polyalcohols, poly amino acids, and other organic polymers. The immunogenic compositions of the invention show the efficacy of a new method for antigenic conjugation. Specifically, a carrier protein and an antigenic

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polysaccharide can be conjugated in the presence of an enzyme from the sortase family of proteins. Thus, the carrier protein can effectively display and facilitate a robust immune response to the antigenic polysaccharide. The immune response to the antigenic polysaccharide can also be enhanced in the immunogenic conjugate relative to the isolated antigenic polysaccharide. Unlike other chemical

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5 conjugations, all immunogenic conjugates produced by the method described herein are homogenous in their structure and thus offer compositions with a high and reproducible specific activity. Thus, the new conjugation procedures can be applied to a wide range of antigens and carrier proteins to provide improved and highly active immunogenic conjugate compositions.

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10 The immunogenic composition of the invention can include an antigen (e.g., a polysaccharide or a whole cell pathogen) covalently linked to a sortase recognition sequence or a carrier protein containing sortase through  $Z^1-C(Z^3)-N(H)-N(H)-(C(O)-(L-C(O)))_n-N(H)-N(H)-m-Z^2$ , where  $Z^1$  is a bond to an oxygen atom in the polysaccharide or a the whole cell pathogen,  $Z^2$  is a bond to a carbonyl group in the sortase recognition sequence or in the a carrier protein containing sortase (e.g., a C-terminal carbonyl, 15 aspartic acid side chain carbonyl, or glutamic acid side chain carbonyl),  $Z^3$  is O or NH, each of n and m is 0 or 1, and L, when present, is c2-6 alkanediyl or c6-10 arenediyl. These immunogenic compositions can be prepared by contacting an antigen-cyanate (e.g., prepared by contacting an antigen with an electrophilic source of cyanide, such as cyanogen bromide or 1-cyano-4-dimethylaminopyridinium tetrafluoroborate (CDAP)) can be contacted with a hydrazine-activated sortase recognition sequence to 20 produce an antigen-sortase recognition sequence conjugate. The antigen-sortase recognition sequence conjugate can be reacted with sortase to produce an antigen-carrier protein conjugate, in which the carrier protein contains sortase.

Polysaccharides are polymers of saccharides (sugars). PS derived from capsules are the 25 primary antigenic components involved in protective immunity against encapsulated bacterial pathogens such as *Neisseria meningitidis*, *Streptococcus pneumoniae*, *Salmonella typhi*, and *Haemophilus influenzae* Type B. Immunization of adolescents and adults with immunogenic conjugates based on microbial PS has been successful in reducing disease burden, but has proven less effective in providing protective immunity to infants and young children (i.e., children less than 24 months of age). Young 30 children have not yet developed a mature adaptive immune repertoire and T cell-independent antigens such as capsular PS are poorly immunogenic and do not lead to long-term protective immune responses (i.e., an immunological memory response) in such young immunogenic conjugate recipients.

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A T-cell independent antigen such as PS can be converted to a T-cell dependent antigen by 35 chemical coupling of PS to protein; this process is called "conjugation" and involves the formation of covalent bonds between atoms in the PS structure and side chain atoms of amino acids present in the "carrier" protein. Such "immunogenic conjugates" more efficiently promote the induction of B-cell maturation and isotype switching leading to much higher levels of antibody with the correct anti-PS protective profile. Protective antibodies have high affinity for their PS antigens, and typically are of the 40 Immunoglobulin G (IgG) subclass, a long-lived antibody with complement fixing and opsonic effector activity.

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A non-limiting pathway for induction of an anti-PS IgG immune response is exemplified by a conjugate made between a PS and the carrier protein tetanus toxoid. In this model, only B-cells that display antibody receptors that recognize the PS bind the PS-carrier protein conjugate. Thus, the carrier protein is bound to the surface of the B-cell that displays the correct PS binding specificity. The carrier

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5 protein-PS complex is taken up by these B-cells into the intracellular vacuolar compartment where the carrier is processed by proteolytic degradation. Peptides derived from the carrier protein are transported and loaded into the presentation groove of the MHC-Class II receptor (MHC-II). This MHC-II-carrier peptide complex is displayed on the surface of the B-cell. Upon recognition of the MHC-II-peptide complex by the T-cell receptor (TCR), T-cells become activated and secrete cytokines that provide "help"

10 for the induction of B-cell differentiation. B-cells expand in numbers and differentiate into "plasma cells" which now secrete antibody. Initially Immunoglobulin M (IgM) is produced by plasma cells but eventually the T-cell help causes the plasma cells to class switch and produce other isotype classes of antibody such as IgG. This process continues with plasma cells undergoing mutational changes leading to production of antibody receptors that have even higher affinity for the PS-carrier protein conjugates. As

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15 antigen is cleared, only the higher affinity plasma cells are activated by residual PS-carrier protein conjugate remaining in circulation. The process of T-cell dependent maturation of plasma cells continues, leading to the expansion of plasma cell populations which produce high affinity antibodies of the IgG class. The expansion can be easily monitored by measuring the levels of anti-PS IgG antibodies in the serum of an immunized subject, e.g., a human.

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Eventually the maturation and switching process leads to the production of Memory B-cells which are long lived and specific for the PS. Memory B-cells have a unique property in that they can be immediately activated if exposed to PS. Activation causes memory B-cells to multiply and quickly produce anti-PS IgG. The activation of memory B cells that occurs during a second exposure of to PS

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25 antigen is called a "booster response" and is indicative of a long lived "secondary" memory immune response. Primary immunization may stimulate the production of IgM antibodies and some IgG antibodies. Upon secondary immunization, i.e., the "booster" shot, memory cells already programmed by the first immunization are stimulated to produce large quantities of IgG, the memory immune response.

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30 A T-cell independent antigen generally does not stimulate lasting immunity, i.e., the production of IgG antibodies, but may stimulate the production of less potent and more temporary IgM antibodies. As such, PS antigens alone do not typically produce booster responses of IgG. However, PS do produce booster responses if primary immunization is performed with a PS-carrier protein conjugate because memory cells induced by the conjugate have already been programmed to produce IgG. Indeed, the

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35 booster response in immunized animals or humans is thought to mimic the protective response due to exposure to a microbe displaying the PS; this long term memory is critical for an immunogenic conjugate to work in protecting immunized subjects years after their immunization with immunogenic conjugates. Thus, PS-carrier protein conjugates are valued for (1) their ability to induce high levels of IgG against PS antigens, and (2) their ability to induce memory immune responses against PS antigens. PS antigens

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40 typically do not display these properties and thus are inferior antigens. The difficulty in synthesizing immunogenic conjugates and their cost of production has slowed the development of immunogenic

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conjugates for many bacterial diseases where an immune response to PS may be protective.

Other T-cell independent antigens include homopolymers of amino acids, such as poly-gamma-D-glutamic acid (PGA), and polyalcohols. Indeed most biological polymers are T-cell independent

5 antigens. Polymers can cross-link Immunoglobulin (Ig) receptors on B-cells that recognize them due to the repetitive nature of their chemical structures (and thus epitopes). Thus polymers can activate B-cells, for production of anti-polymer IgM in the same way that polysaccharides do. For example, an amino acid homopolymer, poly-gamma-D-glutamic acid (PGA) of *Bacillus anthracis*, is a capsular polymer that is poorly immunogenic and also a T-cell independent antigen. Immunogenic conjugates composed of PGA

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10 linked to protein carriers are highly immunogenic, able to induce anti-PGA IgG and immunological memory to PGA. Hence, most polymers respond like PS in terms of their immunogenicity because they cannot be processed and displayed in the context of MHC-II and thus cannot recruit T-cell help. An exception is found in some naturally-occurring polymers that interact with another class of receptor termed Toll-like receptors (TLRs). Once activated, TLRs can induce production of cytokines by host cells

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15 and produce changes in the adaptive immune response. Some PS are covalently attached to TLR ligands or contaminated with such ligands. For example, lipopolysaccharides (LPS) are PS that are highly immunogenic and induce IgG and memory responses; the lipid A moiety of LPS is a TLR ligand and may be responsible for the immunological properties.

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20 Immunogenic conjugates are difficult to produce cheaply because of the specialized chemistry required. PS-carrier protein conjugation by covalent linkage procedures have numerous drawbacks, including the need for organic solvents and other reagents that can adversely affect the structure and/or epitope presentation of carrier proteins; highly specialized chemical linkage reactions to selectively target a reactive site within the target protein; and time-consuming additional processing steps for carrying out

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25 the conjugation. Typically, coupling chemistry must be worked out for various PS that is unique for the chemistry of the PS and the carrier protein that has been selected. This coupling chemistry introduces functional groups in the PS that then can be linked to carrier protein typically through the epsilon amino side chains of lysine residues. For conventional PS-protein immunogenic conjugates, the PS structure, nature of the carrier protein selected, and the type of linkage chemistry can all affect immunogenicity of

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30 the conjugate. As such, for example, in the case of pneumococcal disease where each of the 90+ known serotypes has a different PS structure (Bentley et al., *PLOS Genetics* 2(3):e31 262-269, 2006), one single conjugation method may not be appropriate for all serotypes. Reproducibly synthesizing immunogenic conjugates with reproducible immunological properties involves careful control of the PS structure, the nature of the carrier selected, and the type of linkage chemistry, all of which dramatically increase the

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35 cost of manufacture of immunogenic conjugates. Thus, there is a need for a simplified, reproducible, cost-effective mechanism of producing PS-protein conjugates.

¶The sortase family of bacterial proteins includes well-conserved enzymes encoded by the genomes of numerous Gram positive bacterial organisms. Their enzymatic activity was first described in

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40 *Staphylococcus aureus*. As shown in Fig. 1, naturally occurring sortases modify surface proteins by recognizing and cleaving a carboxyl-terminal recognition signal. For most substrates of sortase enzymes, the recognition signal consists of the motif LPXTG (Leu-Pro-any amino acid (AA)-Thr-Gly), followed by a

highly hydrophobic transmembrane sequence, and a cluster of basic residues such as Arg. Sortase, peptidase activity results in cleavage between the T and G residues of the sortase recognition sequence. Furthermore, a sortase active site, containing a sulfhydryl group within the Cys residue, is exposed to the carboxyl group of the Thr residue, allowing for formation of a thioester bond between C and T residues. A

5 transamidation reaction between the sortase-protein conjugate and a polysaccharide polymer, peptidoglycan, displaying a polyglycine motif results in a covalent linkage between the carboxyl group of the protein and the amino group of the Gly of the polysaccharide. The formation of this peptide bond leads to the covalent attachment of the protein to the bacterial cell wall (Marraffini et al., *Microbiol Mol Biol Rev.* 70: 192-221, 2006).

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Sortases have been classified into four major families, designated sortase A (SrtA), sortase B, (SrtB), sortase C (SrtC), and sortase D (SrtD), respectively, based on sequence alignment and phylogenetic analysis of 61 sortases from Gram-positive bacterial genomes (Dramsi et al., *Res Microbiol.* 156: 289-97, 2005). Sortase A of *Staphylococcus aureus* recognizes a LPXTG like sequence motif

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15 located near the C-terminus of the target proteins, cleaves at the Thr-Gly peptide bond, and catalyzes the formation of a new peptide bond between a threonyl carboxyl and an amino group of the peptidoglycan, pentaglycine cross-bridges (Marraffini et al., *Microbiol Mol Biol Rev.* 70: 192-221, 2006; Ton-That et al., *Proc Natl Acad Sci USA.* 96: 12424-12429, 1999). The immunogenic composition of the invention encompasses embodiments relating to a SrtA, SrtB, SrtC, and/or SrtD from any bacterial species or

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20 strain, as well as evolved sortases that have been modified from their wild type amino acid sequences to include at least one mutation in the encoding sequence, examples of which are provided herein.

The conjugation of an antigen (e.g., a polysaccharide or a whole cell pathogen) to a sortase recognition sequence may be performed using a cyanylation-mediated conjugation method. Specifically,

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25 contacting an antigen-cyanate with a hydrazine-activated sortase recognition sequence can produce a conjugate, where the antigen is linked to the sortase recognition sequence through the linker  $Z^1-C(Z^2)-N(H)-N(H)-(-C(O)-(L-C(O)))_n-N(H)-N(H)-m-Z^2$ , as defined herein. The antigen-cyanate can be prepared through the cyanylation of the antigen with an electrophilic source of cyanide (e.g., cyanogen bromide or CDAP). The hydrazine-activated sortase recognition sequence can be prepared by reacting

30 the sortase recognition sequence with a hydrazine source agent (e.g.,  $H_2N-N(H)-(-C(O)-(L-C(O)))_n-N(H)-N(H)-m-H$ ) under the reaction conditions known in the art for hydrazide formation (e.g., using a coupling agent, such as EDC). For a general description of the cyanylation-mediated conjugation reactions, see *Bioconjugate Techniques*, 3<sup>rd</sup> ed.; eds.: Hermanson; Academic Press, London, UK, incorporated herein by reference. For example, one non-limiting cyanylation-mediated conjugation

35 protocol includes dissolution of a hydrazine source agent (e.g., dicarboxylic acid dihydrazide, such as succinic acid dihydrazide or adipic acid dihydrazide) in about neutral pH phosphate buffer (e.g., pH of 7.2) containing sodium chloride (e.g., about 0.15M sodium chloride), dissolving a sortase recognition sequence in this solution, adding a peptide coupling agent (e.g., 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide (EDC)), and allowing the resulting reaction mixture to react for a

40 sufficient time period (e.g., about 2 to 4 hours). The resulting hydrazine-activated sortase recognition sequence can be purified, e.g., by dialysis or gel filtration using a desalting resin.

The antigen-sortase recognition sequence conjugate can be reacted with a sortase to produce an antigen-carrier protein conjugate, in which the carrier protein contains sortase. The antigen-carrier protein conjugate can then be reacted with another carrier protein, as described herein.

5 Advantageously, preparation of a whole cell-carrier protein conjugates can facilitate the preparation of polysaccharide-carrier protein conjugates, as, after the conjugation, the whole cell-carrier protein conjugate can be subjected to lysing conditions known in the art, and the resulting polysaccharide-carrier protein conjugate can be purified away from the cellular debris and reaction byproducts using, e.g., affinity purification using solid support having affinity for the carrier protein (e.g., if  
10 the carrier protein includes one or more affinity purification tags, or if the solid support includes antibodies specific to the carrier protein).

*Immunogenic Conjugates*

The immunogenic conjugates of the invention have the potent immunological properties of typical  
15 PS-carrier protein immunogenic conjugates but desirably differ from previously known immunogenic conjugates in that an antigen of interest, e.g., PS or capsular organic polymer, may be coupled to a desired carrier protein without utilizing differing chemical linkages specialized to produce each combination. Rather, as depicted in Fig. 2, a novel sortase reaction is performed that is the reverse of a sortase reaction in nature where an antigenic polysaccharide is coupled to a sortase or a carrier protein.

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20 In the immunogenic conjugates of the invention, an antigen of interest, e.g., PS or capsular organic polymers, is covalently linked by a thioester bond to a sortase which is then optionally capable of coupling the antigen with a carrier protein by a peptide bond. For example, a PS-carrier protein conjugate may be formed by first covalently linking a sortase to a soluble antigen, e.g., PS or capsular organic polymers: these immunogenic conjugates are referred to as a PS-sortase immunogenic conjugates (conjugate 1 in  
25 Fig. 2). The novel PS-sortase conjugate may be enzymatically stabilized by chemical cross-linking, for example, such that sortase is the carrier protein of the immunogenic conjugate. Alternatively, an un-stabilized PS-sortase immunogenic conjugate in the presence of a secondary carrier protein may catalyze the covalent linkage between the antigenic PS and the secondary carrier protein to produce a novel PS-carrier protein  
30 conjugate: these immunogenic conjugates are referred to as PS-carrier protein

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30 immunogenic conjugates (conjugate 2 in Fig. 2).

In desirable embodiments, the immunogenic conjugates of the invention include a polysaccharide antigen conjugated to a sortase carrier protein capable of stimulating an immune response. In another desirable  
35 embodiment, the immunogenic conjugates of the invention include a polysaccharide antigen

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35 conjugated to a carrier protein capable of stimulating an immune response.

Immunogenic conjugates of the invention may be prepared by attaching a sortase recognition sequence to a polysaccharide. In the presence of a sortase, the polysaccharide becomes a sortase substrate and is covalently linked to a sortase by a sortase ligation sequence. In desirable embodiments,  
40 the thio-ester linkage between the PS and sortase conjugate may be stabilized to prevent reversal of the covalent bond formed. Methods of enzymatic stabilization by photo cross-linking, e.g., ultraviolet (UV) cross-linking, or chemical cross-linking, e.g., formaldehyde, glutaraldehyde, and

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formaldehyde/glutaraldehyde cross-linking, are well known in the art. Once the PS-sortase immunogenic conjugate is formed, treatment with, for instance, a chemical cross-linker such as formaldehyde, cross-links the basic amino acid lysine residues of sortase, further stabilizing the enzymatic conjugate.

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5 Further, a carrier protein of interest may be attached to a polyglycine motif to enable covalent linkage between itself and the PS. By mixing of the non-cross-linked PS-sortase conjugate with a carrier protein attached to a polyglycine motif, a covalent bond between an antigenic PS and the carrier protein is formed by a sortase ligation sequence, which produces the PS-carrier protein conjugate. By attaching a synthetic peptide to a PS, an antigenic polysaccharide may be covalently linked to any sortase enzyme.

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10 Further, attachment of a polyglycine motif to a carrier protein enables the covalent linkage of an antigenic polysaccharide to any carrier protein, when a first PS-sortase conjugate is formed. Exemplary and preferred carrier proteins and polysaccharide antigens of interest are described herein.

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The methods of making immunogenic conjugates described herein are less complex than  
15 immunogenic conjugate technology because its chemistry depends only on the covalent-linking chemistry of a sortase recognition peptide of the antigenic PS with that of the Cys residue of a sortase active site; or the polyglycine motif of the carrier protein (e.g., DNI, cholera toxin B subunit, diphtheria toxin, tetanus toxin Fragment C, or *Escherichia coli* beta-galactosidase). Furthermore, multiple antigenic polysaccharides can be coupled to a carrier protein; or, a mixture of carrier proteins can be conjugated to  
20 the antigenic PS in a single reaction or multiple sequential reactions. Thus, the method described herein enables multiplexing of the immunogenic conjugate, further reducing the cost of production.

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Immunogenic conjugates of the invention may be made using a combination of a sortase,  
recognition peptide and polyglycine motif, such as, e.g., those described herein, to covalently link any  
25 carrier protein, such as, e.g., those described herein, in the presence of one or more antigens of interest, such as, e.g., those described herein. If one antigen of interest is used, the immunogenic conjugate of the invention is said to be monovalent. If more than one antigen of interest is used, the immunogenic conjugate of the invention is said to be multivalent.

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30 The methods of making immunogenic compositions described herein may be used with any antigenic polysaccharide capable of being covalently linked by a free carboxyl group, e.g., any capsular polymer or any polymer, attached to a sortase recognition peptide, and any carrier protein capable of being covalently-linked by a free amino group, e.g., carrier proteins attached to a polyglycine motif. Tetanus toxoid is one possible carrier protein. This toxin is detoxified by treatment with formaldehyde, a

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35 reagent that reacts with amino groups of proteins. Other desirable carrier proteins include the cholera toxin B subunit (available from SBL Vaccin AB), diphtheria toxin, tetanus toxin Fragment C (available from Sigma Aldrich), DNI, or beta-galactosidase from *Escherichia coli* (available from Sigma Aldrich). Further, immunogenic conjugates of the invention may include whole cell encapsulated pathogens as the antigen,

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40 pathogens may be killed by a chemical, e.g., formaldehyde, treatment or by heat-inactivation and subsequently conjugated to sortase as described herein.

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The immunogenic conjugates of the invention may be used to immunize against, for example, *Pneumococcus* infection, *Streptococcus* (groups A and B) infection, *Haemophilus influenzae* type B ("HiB") infection, meningococcal (e.g., *Neisseria meningitidis*) infection, and may be used as O antigen immunogenic conjugates from Gram negative bacteria (e.g., *Pseudomonas aeruginosa*, *Francisella tularensis* (Thirumalapura et al., *J. Med. Microbiol.* 54:693-695, 2005; Vinogradov and Perry, *Carbohydr. Res.* 339:1643-1648, 2004; Vinogradov et al., *Carbohydr. Res.* 214:289-297, 1991), *Shigella* species, *Salmonella* species, *Acinetobacter* species, *Burkholderia* species, and *Escherichia coli*).

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#### Peptide Linkers

10 Peptide linkers used in the immunogenic conjugates of the invention desirably are polypeptide sequences that are substrates for a sortase enzyme. In a further embodiment, an immunogenic conjugate composition is provided including an antigenic polysaccharide covalently linked to a carrier protein by a peptide bond of a sortase ligation sequence. Desirably, the immunogenic conjugate of the invention has the formula: PS-L-CP, where PS is an antigenic polysaccharide; L is a peptide linker; and

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15 CP is a carrier protein. For example, the covalent linkage between an antigenic polysaccharide and a carrier protein may consist of a peptide bond at the carboxyl-terminus of a synthetic peptide attached to a side chain of an antigenic polysaccharide. Exemplary PS side chain groups capable of attachment include, but are not limited to, vicinal hydroxyls, non-vicinal hydroxyls, carboxyl groups, amino groups and reducing sugar aldehydes. Examples of a synthetic peptide utilized in the present invention include a

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20 sortase recognition sequence with a carboxyl-terminus, such that prior to linkage with the carrier protein, includes a sortase A, B, C or D recognition motif.

For example, such a synthetic peptide may, in certain embodiments, be engineered to include the sortase recognition sequence LPXTG, where X is any amino acid, and includes but is not limited to

25 residues with amino, carboxyl, thiol, halogen, and azide groups, such that these groups may chemically react with an activated polysaccharide. The sortase recognition sequence may be modified to include reactive residues located at the N-terminal of, internal to, or C-terminal of the synthetic peptide, such that the residues allow for covalent modification of a polysaccharide. The sortase recognition sequence of the invention may

30 polysaccharides of the invention may be chemically activated with periodate, cyanogen borohydride, or carbodiimide reagents.

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In other desirable embodiments, a covalently linked polysaccharide to a synthetic peptide is

35 mixed with a sortase enzyme capable of recognizing the peptide sequence. In another desirable embodiment, a sortase enzyme is covalently linked to a polysaccharide by a sortase ligation sequence of LPXT, where X is any amino acid. A peptide linker of the invention may additionally include a polyglycine motif with a peptide sequence of GGGGG. Such a polyglycine motif is covalently bound to a free primary amino group (NH<sub>2</sub>-R) of a desired carrier protein and is recognized by a sortase enzyme. A carrier protein of the invention

40 may encompass a carrier protein further chemically modified to covalently link the

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carrier protein with at least one peptide and/or at least one protein that displays the polyglycine motif. In other desirable embodiments, a covalently linked carrier protein to a polyglycine motif is mixed with a polysaccharide covalently linked to a sortase enzyme that is capable of recognizing the polyglycine motif.

In some embodiments, an antigenic polysaccharide and a carrier protein include the sortase ligation sequence LPXT at the covalent linkage.

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5 In some embodiments, a sortase ligation sequence includes a sortase recognition sequence. In some embodiments, a sortase ligation sequence is located C-terminal of an antigenic PS. In some embodiments, a sortase ligation sequence includes a polyglycine motif of 2, 3, 4 or 5 Gly residues. In some embodiments, a sortase ligation sequence is located N-terminal of a carrier protein. In other embodiments, a sortase ligation sequence is located C-terminal of an antigenic polysaccharide, and N-terminal of a carrier protein. In some embodiments, an immunogenic conjugation includes formation of

10 an amide bond between a C-terminal carboxyl group of a cleaved sortase recognition sequence and an N-terminal amino group of a polyglycine sequence.

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In some embodiments, a sortase recognition sequence is a sortase A recognition sequence, having a consensus sequence  $X_1PX_2X_3G$ , where  $X_1$  is Leu, Ile, Val or Met, P is Pro,  $X_2$  is any amino acid,

15  $X_3$  is Ser, Thr or Ala, and G is Gly. In further embodiments,  $X_2$  is Asp, Glu, Ala, Gln, Lys or Met. In some embodiments, a sortase recognition sequence is a sortase A recognition sequence having the consensus sequence  $LPX_1TG$ , where  $X_1$  is any amino acid. Exemplary sortase A recognition sequences include but are not limited to the following sequences: LPKTG, LPATG, LPNTG, LPETG, LPNAG, LPNTA, LGATG, IPNTG, or IPETG.

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In some embodiments, a sortase recognition sequence is a sortase B recognition sequence having a consensus sequence  $NPX_1TX_2$ , where N is Asn, P is Pro,  $X_1$  is Lys or Gln, T is Thr, and  $X_2$  is Asn, Asp, or Gly. In further embodiments, a sortase B recognition sequence is NPQTN. Exemplary,

25 sortase B recognition sequences include but are not limited to the following sequences: NPKTG, NSKTA,

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NPQTG, NAKTN, or NPQSS

In some embodiments, a sortase recognition sequence is a sortase C recognition sequence and may utilize as its substrate  $LPX_1TX_2$ , where L is Leu, P is Pro, and T is Thr, as a recognition motif, with each  $X_1$

30 and  $X_2$  independently representing any amino acid residue.

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In some embodiments, a sortase recognition sequence is a sortase D recognition sequence. In some embodiments, consensus sequences for sortase D are  $LPX_1TA$  or  $LAX_1TG$ , where L is Leu, P is Pro,  $X_1$  is any amino acid, T is Thr, A is Ala, and G is Gly.

35 Additional embodiments of the immunogenic conjugate may include a combination of any of the above sortase recognition sequences. For example, the invention may include an antigenic polysaccharide covalently linked to at least one sortase recognition sequence. Furthermore, sortase recognition sequences linked to an antigenic polysaccharide may be the same sequence or include any,

40 of the differing sequences, such as recognition sequences provided for SrtA, SrtB, SrtC, and/or SrtD. In

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additional embodiments, an antigenic polypeptide of the invention is covalently linked to at least one carrier protein.

### Carrier Proteins

Carrier proteins used in the immunogenic conjugates of the invention desirably are proteins that, either alone or in combination with an antigen, invoke an immune response in a subject. Desirably, the carrier protein contains at least one epitope recognized by a T-cell. Desirably, the epitope is capable of inducing a T-cell response in a subject, and induce B-cells to produce antibodies against the entire antigen of interest. Epitopes as used in describing this invention, include any determinant on an antigen that is responsible for its specific interaction with an antibody molecule or fragment thereof. Epitopic determinants usually consist of chemically active surface groupings of molecules such as amino acids or sugar side chains and have specific three-dimensional structural characteristics as well as specific charge characteristics. To have immunogenic properties, a protein or polypeptide generally is capable of stimulating T-cells. However, a carrier protein that lacks an epitope recognized by a T-cell may also be immunogenic.

By selecting a carrier protein that is known to elicit a strong immunogenic response, a diverse population of subjects can be treated by an immunogenic conjugate described herein. The carrier protein desirably is sufficiently foreign to elicit a strong immune response to the immunogenic conjugate. Typically, the carrier protein used is a molecule that is capable of imparting immunogenicity to the antigen of interest. In a desirable embodiment, a carrier protein is one that is inherently highly immunogenic. Thus, a carrier protein that has a high degree of immunogenicity and is able to maximize antibody production to the antigens complexed with it is desirable.

Various carrier proteins of the invention include, e.g., toxins and toxoids (chemical or genetic), which may or may not be mutant, such as anthrax toxin, PA and DNI (PharmAthene, Inc.), diphtheria toxoid (Massachusetts State Biological Labs; Serum Institute of India, Ltd.) or CRM 197, tetanus toxin, tetanus toxoid (Massachusetts State Biological Labs; Serum Institute of India, Ltd.), tetanus toxin fragment Z, exotoxin A or mutants of exotoxin A of *Pseudomonas aeruginosa*, bacterial flagellin, pneumolysin, an outer membrane protein of *Neisseria meningitidis* (strain available from the ATCC (American Type Culture Collection, Manassas, Va.)), *Pseudomonas aeruginosa* Hcp1 protein, *Escherichia coli* heat labile enterotoxin, shiga-like toxin, human LTB protein, a protein extract from whole bacterial cells, and any other protein that can be cross-linked by a peptide linker. Desirably, the carrier protein is the cholera toxin B subunit (available from SBL Vaccin AB), diphtheria toxin (Connaught, Inc.), tetanus toxin Fragment C (available from Sigma Aldrich), DNI, or beta-galactosidase from *Escherichia coli* (available from Sigma Aldrich). Other desirable carrier proteins include bovine serum albumin (BSA), P40, and chicken riboflavin. (Unless otherwise indicated, the exemplary carrier proteins are commercially available from Sigma Aldrich.) Other exemplary carrier proteins are MAPs (multi-antigenic peptides), which are branched peptides. By using a MAP, cross-linking density is maximized because of multiple branched amino acid residues. An exemplary amino acid that can be used to form a MAP is, but is not limited to, lysine.

Both BSA and keyhole limpet hemocyanin (KLH) have commonly been used as carriers in the development of immunogenic conjugates when experimenting with animals. Carrier proteins which have been used in the preparation of therapeutic immunogenic conjugates include, but are not limited to, a

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number of toxins of pathogenic bacteria and their toxoids. Examples include diphtheria and tetanus toxins and their medically acceptable corresponding toxoids. Other candidates are proteins antigenically similar to bacterial toxins referred to as cross-reacting materials (CRMs). Carrier proteins of the invention may also include any protein not derived from humans and not present in any human food substance.

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In another embodiment, DNI is used as the carrier protein because it is nontoxic leaving no need to detoxify the protein before use. Furthermore, the use of DNI is desirable because DNI may also induce a protective immune response to *B. anthracis*, in addition to the protective immune response to the antigen of interest.

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A carrier protein may include one or more affinity purification tags. Purification tags are known in the art. Non-limiting examples of the purification tags are poly-His tags (e.g., oligohistidines having from 5 to 10 His repeating units or from 6 to 9 repeating units), FLAG-tag, calmodulin-tag, S-tag, SBP-tag, TC tag, Strep-tag, VSV-tag, Xpress tag, Isopeptag, Halo-tag, GFP-tag, biotin carboxyl carrier protein, chitin binding protein (CBP), maltose binding protein (MBP), glutathione-S-transferase (GST), V5-tag, Myc-tag, and HA-tag.

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Sortases

Other exemplary carrier proteins of the invention include members of the sortase family of enzymes because sortases may also induce a protective immune response to Gram-positive bacterium in addition to the protective immune response to the antigen of interest. A sortase carrier protein may be derived from a sortase A, sortase B, sortase C, or sortase D. Carrier proteins of the invention may also include a catalytically active fragment, derivative, or variant of a sortase A, sortase B, sortase C, or sortase D. For example, the carrier protein of the invention may include a soluble fragment of sortase A

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including the C-terminal catalytic domain. In another exemplary embodiment, the carrier protein of the invention may include a central catalytic domain of a sortase B.

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Examples of suitable sortases are described in Dramsi et al., *Res. Microbiol.* 156:289-297, 2005; Comfort et al., *Infect. Immun.*, 72:2710-2722, 2004; Chen et al., *Proc. Natl. Acad. Sci. USA.* 108: 11399-

11404, 2011 ; and Pallen et al., *Trends in Microbiology.* 9: 97-101, 2001, the entire contents of each of

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which are incorporated herein by reference. The sortase carrier protein may also be isolated from but not limited to one of the following bacterial strains: *Bacillus anthracis*, *Bacillus cereus*, *Bacillus halodurans*, *Clostridium acetobutylicum* (SortaseD), *Clostridium perfringens*, *Clostridium tetani* (SortaseD), *Enterococcus faecalis*, *Lactobacillus plantarum*, *Lactococcus lactis*, *Listeria innocua*, *Listeria monocytogenes*, *Staphylococcus aureus*, *Staphylococcus epidermis*, *Streptococcus agalactiae*, *Streptococcus gordonii*, *Streptococcus mutans*, *Streptococcus pneumoniae*, *Streptococcus pyogenes*, and *Streptococcus suis*.

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The sequences of many sortases and of the naturally occurring nucleic acids that encode them are found in publicly available databases such as those of the National Center for Biotechnology Information (NCBI) available at Entrez (<http://www.ncbi.nlm.nih.gov/Entrez>), e.g., GenBank. The

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sequences of sortase proteins having the accession numbers provided herein are hereby incorporated by reference.

The carrier protein of the invention may include a sortase A derived from class A sortases, e.g.,

5 S. aureus sortase A. The prototypical class A sortase, *S. aureus* sortase A, has been purified and characterized (Ton-That et al., *Proc. Natl. Acad. Sci. USA*. 96:12424-12429, 1999), and the gene that encodes it has been cloned and sequenced (Mazmanian, et al., *Science*. 285:760-763, 1999.) The gene has been assigned accession number AF162687, and the protein sequence has accession number AAD48437.1.

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Additional exemplary sequences of class A sortases from a variety of other bacterial

10 species are available under the following GenBank accession numbers: *S. pyogenes* (Spyog) SrtA, AAK34025; *S. gordonii* (Sgord) SrtA, AAG41778; *L. lactis* (Llact) hypO, AAK0521 1 ; *S. aureus* (Saure), SrtA, AAD48437; and *A. naeslundii* (Anaes) fimbria-associated protein (fimassoc), AAC13546; *Staphylococcus aureus* subsp. *aureus* MSSA476, CAG44229.

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15 In additional embodiments, the carrier protein of the invention features a sortase B derived from class B sortases identified from the *Streptococcus*, *Bacillus*, *Staphylococcus*, *Clostridia*, and *Listeria* genera, among others. Exemplary sequences of several class B sortases are available at GenBank accession numbers as follows: *S. pyogenes*, NP 268518; *B. anthracis*, NP 846988; *C. perfringens*, NP 561429; *E. faecalis*, AAQ16264; *Staphylococcus aureus* subsp. *aureus* MRSA252, CAG401 10; *L.*

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20 *monocytogenes*, CAD00259.

The carrier protein of the invention may include a sortase C derived from class C sortases found among species in the *Streptococcus*, *Enterococci*, *Bacillus*, and *Clostridia* genera. Exemplary sequences of several class C sortases are available under the following accession numbers: *S. pyogenes*, AAL1

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25 1468; *C. diphtheriae*, NP 940532.1; *Streptococcus suis*, BAB83966.

In some embodiments, the invention features a sortase D carrier protein derived from class D sortases found among species in the *Streptomyces*, *Corynebacterium*, *Clostridium*, and *Bacillus* genera. Sequences of several class D sortases are available under the following accession numbers:

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30 *Streptomyces coelicolor*, NP 628037; *B. subtilis*, CAB12748, *C. tetani*, NP 781831.

The amino acid sequences of sortases and the nucleotide sequences that encode them are known to those of skill in the art and are disclosed in a number of references cited herein, the entire contents of all of which are incorporated herein by reference. Those of skill in the art will appreciate that

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35 any sortase and any sortase recognition motif can be used in some embodiments of this invention, including, but not limited to, the sortases and sortase recognition motifs described in Ploegh et al.,

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International PCT Patent Application, PCT/US2010/000274, filed Feb. 1, 2010, published as WO/2010/087994 on Aug. 5, 2010 (e.g., paragraphs [0089]-[0101]); and Ploegh et al., International Patent Application PCT/US2011/033303, filed Apr. 20, 2011, published as WO/2011/133704 on Oct. 27,

40 2011 (e.g., paragraphs [0085-0094]); the entire contents of each of which are incorporated herein by reference.

The carrier protein of the invention may also include evolved sortases. An evolved sortase exhibits enhanced reaction kinetics, for example, in that it catalyzes a transpeptidation reaction at a greater speed or turnover rate than the respective wild type sortase. An evolved sortase may exhibit a modified substrate preference, for example, in that it utilizes a different substrate (e.g., a polypeptide comprising an altered sortase recognition sequence) or binds a given substrate with higher or lower affinity, or with higher or lower specificity than the respective wild type sortase. For instance, the evolved sortase recognizes a sortase recognition sequence that the respective wild type sortase does not recognize or bind. See, e.g., Liu et al., United States Patent Application, 13/922,812, filed Jun. 20, 2013, published as US2014/0057317A1 on Feb. 27, 2014, the entire contents of each of which are incorporated herein by reference, for exemplary sortases, recognition motifs, reagents, and methods for directed evolution of bond-forming sortases.

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For example, some embodiments of the invention provide a sortase comprising a polypeptide sequence of *S. aureus* Sortase A (SEQ ID NO: 1) that is homologous to the polypeptide sequence of a wild type Sortase A (NP\_647265.1), or a fragment thereof, as provided below:

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SEQ ID NO: 1:

MKKWTNRLMTIAGVLLILVAAYLFAKPHIDNYLHDKDKDEKIEQYDKNVKEQASKDKKQAKPQIPKDKSK  
VAGYIEIPDADIKEPVYPGPATPEQLNRGVSF AEENESLDDQNISIAGHTFIDRPNYQFTNLKAAKKGSMVY  
FKVGNETRYKMTSIRDVKPTDVEVLDEQKGKDKQLTLITCDDYNEKTVWEKRKIFVATEVK.

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In some embodiments, the polypeptide sequence of the provided sortase may include one or more amino acid mutations as compared to the wild type sequence of the respective sortase (e.g., the sequence of SEQ ID NO: 1). For example, the evolved sortase sequence provided may include 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 25, or more mutations. In some embodiments, the polypeptide sequence of the provided sortase is at least 90% identity (e.g., 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, 99%, or 99.5%) to a wild type sortase sequence (e.g., the sequence of SEQ ID NO: 1).

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For example, in a desirable embodiment of the invention an evolved *S. aureus* sortase A is provided. An evolved sortase A, or a fragment thereof, may include a mutation relative to the sequence of SEQ ID NO: 1 described herein, for example, P86L, P94S, P94R, N98S, A104T, E106G, A118T, F122S, F122Y, D124G, N127S, K134R, F154R, D160N, D165A, K173E, G174S, K177E, I182V, K190E, or K196T, or any combination of any one of these mutations. In some embodiments, an evolved sortase is provided herein that includes 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, or all 19 of these

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mutations. The aforementioned amino acid substitution may provide an evolved sortase that efficiently uses substrates not bound by the respective parent wild type sortase. For example, in some embodiments, an evolved sortase is provided that is derived from a wild type *S. aureus* sortase A as the parent sortase A, which utilizes substrates including a C-terminal sortase recognition motif of the sequence LPXTG and substrates including an N-terminal polyglycine motif in a transpeptidation reaction.

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In some embodiments, the evolved sortases utilize a substrate different from those used by the parent sortase, e.g., substrates including a C-terminal LPXS, LAXT, LAXTG, MPXT, MPXTG, LAXS, LAXSG, NPXT, NPXTG, NAXT, NAXTG, NAXS, NAXSG, LPXP, LPXPG, or LPXTA motif.

Antigens of Interest

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The composition of the immunogenic conjugate of the invention and methods of making and administering such immunogenic conjugates can be used for any antigen of interest, e.g., a

5 polysaccharide, polyalcohol, or poly amino acid. Desirably, the antigen of interest carries no primary groups that can be destroyed by the chemical reactions employed by the method of making immunogenic conjugates, e.g., the denaturing of an antigen caused by the destruction of antigen disulfide bonds by borohydride reduction. In yet other desirable embodiments of the invention, the antigen of interest is an organic polymer consisting of monomers having at least three atoms, where each of the atoms is

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10 independently selected from carbon, oxygen, hydrogen, phosphate, nitrogen, and sulfate. Exemplary antigens of interest include organic polymers such as polysaccharides (e.g., polysaccharides having at least 18 residues), phosphopolysaccharides, polysaccharides with amino sugars with N-acetyl substitutions, polysaccharides containing sulfonated sugars, other sulfate-modified sugars, or phosphate-modified sugars, polyalcohols, poly amino acids, teichoic acids, or side chains of

15 lipopolysaccharides.

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Exemplary antigens of interest also include capsular organic polymers including those synthesized by microbes, e.g., bacteria, fungi, parasites, and viruses, and then purified from such a biological source using standard methods. Exemplary antigens of interest include microbial capsular

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20 organic polymers including those purified from bacterial organisms such as *Bacillus* species (including *B. anthracis*) (Wang and Lucas, *Infect. Immun.* 72(9):5460-5463, 2004), *Streptococcus pneumoniae* (Bentley et al., *PLoS Genet.* 2(3):e31, Epub 2006; Kolkman et al., *J. Biochemistry* 123:937-945, 1998; and Kong et al., *J. Med. Microbiol.* 54:351-356, 2005), *Shigella* (Zhao et al., *Carbohydr. Res.* 342(9):1275-1279, Epub 2007), *Haemophilus influenzae*, *Neisseria meningitidis*, *Staphylococcus aureus*,

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25 *Salmonella*, (including *Salmonella typhi*), *Streptococcus pyogenes*, *Escherichia coli* (Zhao et al., *Carbohydr. Res.* 342(9):1275-1279, Epub 2007), *Francisella tularensis*, and *Pseudomonas aeruginosa*, and fungal organisms such as *Cryptococcus* and *Candida*, as well as many other microorganisms (see, e.g., Ovodov, *Biochemistry (Mosc.)* 71(9):937-954, 2006; Lee et al., *Adv. Exp. Med. Biol.* 491:453-471, 2001; and Lee, *Mol. Immunol.* 24(10):1005-1019, 1987). Exemplary antigens of interest also include

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30 polymers that do not occur in nature and thus are non-biological in origin.

In other particularly desirable embodiments, the *Francisella tularensis* polysaccharide is the 0 antigen. Desirably, the microbial capsular polymer is poly-gamma-D-glutamic acid (PGA) from *Bacillus anthracis*. In desirable embodiments of the invention, the *Streptococcus pneumoniae* polysaccharide is one of capsular types described in Kong et al. (*J. Med. Microbiol.* 54:35-356, 2005). For example,

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35 *Streptococcus pneumoniae* polysaccharide capsular type desirably is 1 (e.g., 1-g or 1-q), 2 (e.g., 2-g, 2-q, or 2-41 A), 3 (e.g., 3-g, 3-q, 3-c, or 3-nz), 4, 5 (e.g., 5-q, 5-c, 5-qap, or 5-g), 6A (e.g., 6A-g, 6A-cl, 6A-c2, 6A-n, 6A-qap, 6A-6B-g, 6A-6B-q, or 6A-6B-s), 6B (e.g., 6B-c, 6A-6B-g, 6A-6B-q, or 6A-6B-s), 7F (e.g., 7F-7A), 7A (e.g., 7A-cn or 7F-7A), 7B (e.g., 7B-40), 7C (e.g., 7C-19C-24B), 8 (e.g., 8-g or 8-s), 9A (e.g., 9A-9V), 9L, 9N, 9V (e.g., 9A-9V), 9V and 14, 10F (e.g., 10F-q, 10F-ca, or 10F-IOC), 10A (e.g., 10A-17A

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40 or 10A-23F), 10B (e.g., 10B-IOC), HF, I IA (e.g., I IA-nz or 11A-11D-18F), HB (e.g., 1 IB-11C), HC (e.g., 1 IB-11C or HC-cn), HD (e.g., 11A-11D-18F), 12F (e.g., 12F-q or 12F-12A-12B), 12A (e.g., 12A-cn, 12A-46,

or 12F-12A-12B), 12B (e.g., 12F-12A-12B), 13 (e.g., 13-20), 14 (e.g., 14-g, 14-q, 14-v, or 14-c), 15F (e.g., 15F-cn1 or 15F-cn2), 15A (e.g., 15A-cal, 15A-ca2, or 15A-chw), 15B (e.g., 15B-C, 15B-15C, 15B-15C-22F-22A), 15C (e.g., 15C-ca, 15C-ql, 15C-q2, 15C-q3, 15C-S, 15B-15C, or 15B-15C-22F-22A), 16F (e.g., 16F-q or 16F-nz), 16A, 17F (e.g., 17F-n and 17F-35B-35C-42), 17A (e.g., 17A-ca or 10A-17A), 18F (e.g., 18F-ca, 18F-W, or 1 IA-I ID- 18F), 18A (e.g., 18A-nz or 18A-q), 18B (e.g., 18B-18C), 18C (e.g., 18B-18C), 19F (e.g., 19F-gl, 19F-g2, 19F-g3, 19F-q, 19F-n, or 19F-C), 19A (e.g., 19A-g, 19A-, or 19A-ca), 19B, 19C (e.g., 19C-cn1, 19C-cn2, or 7C- 19C-24B), 20 (e.g., 13-20), 21 (e.g., 21-ca or 21-cn), 22F (e.g., 15B-15C-22F-22A), 23F (e.g., 23F-C, 10A-23F, or 23F-23A), 23B (e.g., 23B-C or 23B-q), 24F (e.g., 24F-cn1, 24F-cn2, or 24F-cn3), 24A, 24B (e.g., 7C-19C-24B), 25F (e.g., 25F-38), 25A, 27, 28F (e.g., 28F-28A or 28F-cn), 28A (e.g., 28F-28A), 29 (e.g., 29-ca or 29-q), 31, 32F (e.g., 32F- 32A), 32A (e.g., 32A-cn or 32F-32A), 33F (e.g., 33F-g, 33F-q, 33F-chw, 33F-33B, or 33F-33A-35A), 33A (e.g., 33F-33A-35A), 33B (e.g., 33B-q, 33B-s, or 33F-33B), 33D, 34 (e.g., 34-ca or 34s), 35F (e.g., 35F-47F), 35A (e.g., 33F-33A-35A), 35B (e.g., 17F- 35B-35C-42), 36, 37 (e.g., 37-g or 37-ca), 38 (e.g., 25F-38), 39 (e.g., 39-cn1 or 39-cn2), 40 (e.g., 7B-40), 41 F (e.g., 41 F-cn or 41 F-s), 41A (e.g., 2-41A), 42 (e.g., 17B-35B-35C- 42), 43, 44, 45, 46 (e.g., 46-s or 12A-46), 47F (e.g., 35F-47F), 47 A, 48 (e.g., 48-cn1 or 48-cn2), or GenBank Accession Number AF532714 or AF532715.

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Alternatively, exemplary antigens of interest include killed whole cell encapsulated pathogens such as *Bacillus* species (including *B. anthracis*) (Wang and Lucas, *Infect. Immun.* 72(9):5460-5463, 2004), *Streptococcus pneumoniae* (Bentley et al., *PLoS Genet.* 2(3):e31, Epub 2006; Kolkman et al., *J. Biochemistry* 123:937-945, 1998; and Kong et al., *J. Med. Microbiol.* 54:351-356, 2005), *Shigella* (Zhao et al., *Carbohydr. Res.* 342(9):1275-1279, Epub 2007), *Haemophilus influenzae*, *Neisseria meningitidis*, *Staphylococcus aureus*, *Salmonella*, (including *Salmonella typhi*), *Streptococcus pyogenes*, *Escherichia coli* (Zhao et al., *Carbohydr. Res.* 342(9):1275-1279, Epub 2007), *Francisella tularensis*, and *Pseudomonas aeruginosa*, and fungal organisms such as *Cryptococcus* and *Candida*, as well as many other microorganisms (see, e.g., Ovodov, *Biochemistry* (Mosc.) 71(9):937-954, 2006; Lee et al., *Adv. Exp. Med. Biol.* 491:453-471, 2001; and Lee, *Mol. Immunol.* 24(10):1005-1019, 1987). Whole cell pathogens may contain, but are not limited to, one or more of the aforementioned antigens of interest, e.g., microbial capsular organic polymers, O-antigen, and PGA.

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Immunogenic Conjugate Compositions: antigenic PS-carrier protein

The immunogenic conjugates of the invention may be used in combination, for example, in pediatric immunizations. In addition, the immunogenic conjugates of the invention may be used to immunize against, for example, *Pneumococcus* infection, *Haemophilus influenzae* type B ("HiB") infection, *Streptococcus* (groups A and B) infection, meningococcal (e.g., *Neisseria meningitidis*) infection, and may be used as O antigen immunogenic conjugates from Gram negative bacteria (e.g., *Pseudomonas aeruginosa*, *Francisella tularensis*, *Shigella* species, *Salmonella* species, *Acinetobacter* species, *Burkholderia* species, and *Escherichia coli*).

The immunogenic conjugate formulation desirably includes at least one carrier protein, at least one antigen of interest, and a pharmaceutically acceptable carrier or excipient (e.g., aluminum phosphate, sodium chloride, or sterile water). An immunogenic conjugate composition may also include an adjuvant

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The immunogenic conjugates of the invention may be used in combination, for example, in pediatric immunizations. In addition, the immunogenic conjugates of the invention may be used to immunize against, for example, *Pneumococcus* infection, *Haemophilus influenzae* type B ("HiB") infection, *Streptococcus* (groups A and B) infection, meningococcal (e.g., *Neisseria meningitidis*) infection, and may be used as O antigen immunogenic conjugates from Gram negative bacteria (e.g., *Pseudomonas aeruginosa*, *Francisella tularensis*, *Shigella* species, *Salmonella* species, *Acinetobacter* species, *Burkholderia* species, and *Escherichia coli*).

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The immunogenic conjugate formulation desirably includes at least one carrier protein, at least one antigen of interest, and a pharmaceutically acceptable carrier or excipient (e.g., aluminum phosphate, sodium chloride, or sterile water). An immunogenic conjugate composition may also include an adjuvant

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system for enhancing the immunogenicity of the formulation, such as oil in a water system and other systems known in the art or other pharmaceutically acceptable excipients. A carrier protein-antigenic PS complex that is insoluble under physiological conditions is desirable to slowly release the antigen after administration to a subject. Such a complex desirably is delivered in a suspension containing pharmaceutically acceptable excipients. However, the carrier protein-antigenic PS complex may also be soluble under physiological conditions.

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Typically the immunogenic conjugate is in a volume of about 0.5 mL for subcutaneous injection, 0.1 mL for intradermal injection, or 0.002-0.02 mL for percutaneous administration. A 0.5 ml dose of the immunogenic conjugate may contain approximately 2-500 pg of the antigen covalently linked with approximately 2-500 pg of the carrier protein. In a desirable embodiment, in a 0.5 ml dose, approximately 10 pg of the antigen are conjugated with approximately 10 pg of the carrier protein. The molar ratio of antigen to carrier protein desirably is 1:1 (e.g., 1 part antigen to 1 part carrier protein).

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If there is a concern that the peptides or conjugates may be degraded in the stomach, the immunogenic conjugate may be administered parenterally (for instance, by subcutaneous, intramuscular, intravenous, or intradermal injection). While delivery by a means that physically penetrates the dermal layer is desirable (e.g., a needle, airgun, or abrasion), the immunogenic conjugates of the invention can also be administered by transdermal absorption.

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In particular, the immunogenic conjugates of the invention may be administered to a subject, e.g., by intramuscular injection, intradermal injection, or transcutaneous immunization with appropriate immune adjuvants. Immunogenic conjugates of the invention may be administered, one or more times, often including a second administration designed to boost production of antibodies in a subject to prevent infection by an infectious agent. The frequency and quantity of immunogenic conjugate dosage depends on the specific activity of the immunogenic conjugate and can be readily determined by routine experimentation. While the age at which the first dosage is administered generally is two-months, an immunogenic conjugate may be administered to infants as young as six weeks of age. For children who are beyond the age of a routine infant vaccination schedule, the immunogenic conjugates of the invention

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may be administered according to the following exemplary schedule.

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Age of first dosage	Dosage schedule
6 weeks-5 years of age	Total of four 0.5 ml doses; the first three at least eight weeks apart and the fourth at least six months after the third dose.
6-17 years of age	One 0.5 ml dose.
50 years of age and older	One 0.5 ml dose.

A booster dose is desirably given as early as four years following the last dose in subjects who are at a high risk for infection; or 10 years after the last dose to previously immunized adults and children above fifteen years of age.

The formulations may be presented in unit-dose or multi-dose containers, for example, sealed ampoules and vials and may be stored in a freeze-dried (lyophilized) condition requiring only the addition of the sterile liquid carrier immediately prior to use. Immunogenic conjugates of the invention can be formulated in pharmacologically acceptable vehicles, e.g., alum hydroxide gel, adjuvant preparation, or saline, and then administered, e.g., by intramuscular injection, intradermal injection, or transcutaneous immunization with appropriate immune adjuvants.

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Immunogenic Conjugate Compositions: whole cell pathogen-carrier protein

The immunogenic conjugates of the invention may be used in combination, for example, in pediatric immunizations. In addition, the immunogenic conjugates of the invention may be used to immunize against, for example, *Pneumococcus* infection, *Haemophilus influenzae* type B ("HiB") infection, *Streptococcus* (groups A and B) infection, meningococcal (e.g., *Neisseria meningitides*) infection, and may be used as O antigen whole cell pathogen immunogenic conjugates from Gram negative bacteria (e.g., *Pseudomonas aeruginosa*, *Francisella tularensis*, *Shigella* species, *Salmonella* species, *Acinetobacter* species, *Burkholderia* species, and *Escherichia coli*).

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For whole cell pathogen immunogenic conjugates, the formulation includes at least one inactivated whole cell pathogen including the antigenic polysaccharide of interest, at least one carrier protein, and a pharmaceutically acceptable buffer (e.g., bicarbonate buffer) to neutralize gastric acid. In this formulation, the immunogenic conjugate preparation is mixed with a buffer, e.g., 5.6 g of sodium hydrogen carbonate granules dissolved in 150 mL of sterile water.

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Typically the immunogenic conjugate contains about 1 mg of whole cell pathogen immunogenic conjugate in a single dose for oral administration. A 1 mg dose of the immunogenic conjugate may contain at least  $1 \times 10^9$  whole cell pathogens or a range of  $1 \times 10^9$  to  $1 \times 10^{11}$  whole cell pathogens covalently linked with approximately 2-500 µg of the carrier protein.

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In particular, the immunogenic conjugates of the invention may be administered to a subject enterally (for instance, by oral administration) by ingestion of an immunogenic conjugate in the form of a e.g., liquid, powder, capsule, or tablet. Immunogenic conjugates of the invention may be administered, one or more times, often including a second administration designed to boost production of antibodies in a subject to prevent infection by an infectious agent. The frequency and quantity of immunogenic conjugate dosage depends on the specific activity of the immunogenic conjugate and can be readily determined by routine experimentation. The age at which the first dosage is administered generally is two-years. The immunogenic conjugates of the invention may be administered according to the following exemplary schedule.

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Age of first dosage	Dosage schedule
2 — 6 years of age	Three oral doses at least one week apart.
6 years of age and older	Two oral doses at least one week apart.

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A booster dose is desirably given as early as six months following the last dose in subjects who are at a high risk for infection; or five years after the last dose to previously immunized adults and children above two years of age.

The invention also includes kits that include an immunogenic conjugate described herein. The 5 kits of the invention can also include instructions for using the kits in the immunization methods described herein.

10 The efficacy of the immunization schedule may be determined by using standard methods for measuring the antibody titer in the subject. In general, mean antibody titers (desirably IgG titers) of approximately 1 µg/ml are considered indicative of long-term protection.

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The antigenic polysaccharide-carrier protein complexes for use in the immunogenic conjugate, 15 compositions described herein are desirably between 10 nm and 100 µm in diameter. Viruses can be 100 nm in diameter and are immunogenic. Whole bacteria are 1-10 µm in diameter and are also immunogenic. A small clump of bacteria can be about 100 µm in diameter. In particular embodiments, an antigenic polysaccharide-carrier protein complex in an immunogenic conjugate composition desirably is between 100 nm and 10 µm in diameter. This complex may be soluble or insoluble.

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20 The invention is described herein below by reference to specific examples, embodiments and figures, the purpose of which is to illustrate the invention rather than to limit its scope. The following examples are not to be construed as limiting.

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### EXAMPLES

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#### 25 Example 1: Sortase-mediated Immunogenic Conjugate 1 Preparations

An immunogenic conjugate can be prepared from an antigenic polysaccharide (PS) displaying a sortase recognition peptide and a sortase. For this reaction, polysaccharides are first 30 chemically activated with periodate, cyanogen borohydride, or carbodiimide reagents to allow for attachment of a sortase recognition peptide to PS using conventional chemistry. The sortase recognition peptide is a synthetic peptide that displays the LPXTGXX sequence but which then has unique N-terminal, internal, or C-terminal residues that allow for the covalent modification of activated polysaccharides. The chemical groups of these residues include amino, carboxyl, thiol, halogen, and 35 azide groups, as well as others. These chemical groups are selected to react with activated PS. Once modified, the PS covalently linked to the sortase recognition peptide is mixed with a sortase, for instance SrtA, to covalently attach sortase to the PS by a thioester bond. This reaction produces a PS-sortase conjugate (Fig. 2 conjugate 1). To prevent reversal of the sortase-PS thioester bond, the PS-sortase conjugate may be enzymatically stabilized by treatment with a chemical cross-linking agent such as 40 formalin or glutaraldehyde, further entrapping the antigenic polysaccharide to form a protein cross-linked cage or mesh. To cross-link the antigenic PS-sortase immunogenic conjugate, a 10% neutral buffered formalin is prepared by diluting a 37% aqueous formaldehyde solution with phosphate buffered saline (PBS) to about 3.7-4.0% formaldehyde. The PS-sortase immunogenic conjugate is treated with excess

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10% formalin for about 10 minutes at room temperature to cross-link the antigen to the sortase. Subsequently, the fixation is quenched by addition of excess 1.25 M glycine in PBS.

**Example 2: Sortase-mediated Immunogenic Conjugate 2 Preparations**

5 An immunogenic conjugate can be prepared from an antigenic polysaccharide (PS) displaying a sortase recognition peptide and a carrier protein. For this reaction, polysaccharides are first chemically activated with periodate, cyanogen borohydride, or carbodiimide reagents to allow for attachment of a sortase recognition peptide to PS using conventional chemistry. The sortase recognition peptide is a synthetic peptide that displays the LPXTGX sequence but which then has unique N-terminal, internal, or

10 C-terminal residues that allow for the covalent modification of activated polysaccharides. The chemical groups of these residues include amino, carboxyl, thiol, halogen, and azide groups, as well as others. These chemical groups are selected to react with activated PS. Once modified, the PS covalently linked to the sortase recognition peptide is mixed with a sortase, for instance SrtA, to covalently attach sortase to the PS by a thioester bond. This reaction produces a PS-sortase conjugate (Fig. 2 conjugate 1).

15 A second immunogenic conjugate can be prepared from conjugate 1. For this reaction, a carrier protein is engineered to display polyglycine motif, where at least two glycine repeats are coupled to a carrier protein amino acid residue by a peptide bond. The carrier protein may be modified with glycine repeats by sandwiching the glycine repeats between the carrier protein and a small ubiquitin-like modifier

20 (SUMO) peptide. SUMOylation occurs when the C-terminal carboxyl group of a double-glycine motif in SUMO and the epsilon-amino group of a lysine residue in a carrier protein form an isopeptide bond. Upon addition of the SUMO protease that recognizes the SUMO peptide, the SUMO protease cleaves immediately following the glycine repeat precursor at the C-terminus of the SUMO peptide. This reaction produces a polyglycine-modified carrier protein. The polyglycine decorated carrier protein is

25 subsequently mixed with the PS-sortase conjugate (Fig. 1 conjugate 1) and sortase transfers itself off the recognition peptide modified PS and attaches the polyglycine modified carrier protein to the PS. Thus, this reaction produces a second PS-carrier protein conjugate (Fig. 2 conjugate 2) that is covalently linked by a peptide bond.

30 **Example 3: Whole cell bacterial conjugate and oral administration**

The sortase-mediated immunogenic conjugation method can be performed *in situ* on the surface of the polysaccharide-encapsulated organism, such as *Streptococcus pneumoniae*. For instance, about  $10^9$ - $10^{11}$  cells of 23 *S. pneumoniae* serotypes (1, 2, 3, 4, 5, 6B, 7F, 8, 9N, 9V, 10A, 11A, 12F, 14, 15B, 17F, 18C,

35 for 30 minutes. Alternatively, the cells may be chemically-inactivated by treatment with 55  $\mu$ L of 10% neutral buffered formalin per 1 mL of bacterial cell suspension. The cells are incubated in formalin for at 37° C for one hour. Subsequently, the inactivated cells are washed in PBS and or additional gentle biologically compatible buffers and reagents. The killed cells are then modified to attach the sortase recognition peptide to the surface polysaccharides of the cells. By this approach, the polysaccharide

40 purification and characterization steps are eliminated, and the whole cells conjugated to sortase or the carrier protein(s) of interest are incorporated into the immunogenic conjugate essentially as described in Example 1 or Example 2. The 23 valent pneumococcal whole cell immunogenic conjugate can be

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absorbed mucosally and thus allows for oral administration of the preparation.

Example 4: Generation and Characterization of Sortase-mediated Immunogenic Conjugates

5 The sortase-mediated immunogenic conjugation method can be applied to capsular antigens of various structures and ionic charges. For example, generation of an immunogenic conjugate against *Streptococcus pneumoniae* can be produced by first purchasing 23 types of *Streptococcus pneumoniae* PS from the American Type Culture Collection (ATCC), which are manufactured by Merck, Inc. These PS vary widely in their molecular structure and include PS that are strongly anionic, partially cationic, neutral in charge, phosphorylated, linear, have branching structures, and modified in various other ways. A 10 subset of these PS correspond to the thirteen capsular types in the Wyeth product *Prevnar13*® (1, 3, 4, 5, 6A, 6B, 7F, 9V, 14, 18C, 19A, 19F, and 23F) and can be assayed for their ability to induce IL-6 production by mouse macrophages. Since PS can also be contaminated with a TLR agonist, phenol extraction and ethanol precipitation can be performed to "clean up" (remove residual unknown TLR agonists) commercially prepared *S. pneumoniae* PS.

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15 Removal of the contaminants is confirmed by testing the treated PSs for induction of IL-6 by peritoneal macrophages by standard methods. PSs that are devoid of IL-6 induction activity are used for production of immunogenic conjugates. Following examination of the 23 pneumococcal PS, each of the 23 capsular types is used to make an immunogenic conjugate using a sortase, essentially by the method 20 described in Example 1. A one to one ratio of PS to a dominant negative mutant (DNI) carrier protein is used (approximately 1:1 by dry weight) for these initial immunogenic conjugate preparations. Each preparation is characterized by SDS-PAGE for evidence of covalent-linkage between pneumococcal PS and a carrier protein such as DNI. For some capsular types (e.g., 6B and 23F), other carrier proteins are used to make 25 immunogenic conjugates.

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25 For example, ten different immunogenic conjugates using five different matrix proteins and two different antigens are made as follows. The selection of the five matrix proteins is based on their current use in FDA-approved vaccines or other properties that allow them to serve as tracers for measuring the stability of immunogenic conjugate preparations. The following matrix proteins are used (1) cholera toxin 30 B subunit (available from SBL Vaccin AB), (2) diphtheria toxin, (3) tetanus toxin Fragment C, "Frag C" (available from Sigma Aldrich), (4) DNI, and (5) beta-galactosidase from *Escherichia coli* (available from Sigma Aldrich). As capsular antigens poly-D-glutamic acid from *Bacillus anthracis* and *Streptococcus pneumoniae* capsule type 14 (Suarez et al., *Appl. Environ. Microbiol.* 67:969-971, 2001) are used. Each capsule antigen is combined with each of the five selected matrix proteins to produce 10 distinct 35 immunogenic conjugates. All immunogenic conjugate preparations that show evidence of covalent protein linkage (e.g., in SDS-PAGE) are tested for their immunogenicity.

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40 Immunogenic conjugates can be tested for their ability to induce, in mice, isotype antibody switching to IgG as is observed in conventional conjugate vaccines. All antigens can be absorbed to alum and then typically groups of 5 mice per immunogenic conjugate preparation are used. Mice are pre- 45 pared to obtain baseline immune responses to the test antigens. Mice are then immunized three times (at day 0, 7, 14) by a standard IP injection protocol, and blood is collected at days 10, 20, 30, and 60 days

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post primary immunization. Mouse sera are analyzed by standard ELISA assay for IgG against the PS and carrier proteins used. In these experiments, control groups of mice immunized with only PS are included to assess the ability of various immunogenic conjugate preparations to induce anti-PS IgG, compared with the non-conjugated PS which should be poorly- or non-immunogenic. Promising immunogenic conjugates (i.e., immunogenic conjugates that induce high levels of IgG against PSs) undergo more careful immunological analysis, which seeks to establish the kinetics and dose response aspects of the immune response to the immunogenic conjugate in mice.

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Alternatively, promising immunogenic conjugates and their corresponding controls can be sent to commercial vendors for production of rabbit anti-sera. Similar immunoassays are performed to assess the immunogenicity, class of antibody induced, and kinetics of immune response in rabbits. In these experiments the control is the commercial product *Prevnar130* which is an alum absorbed mixture of 13 different conventional conjugate PS vaccines coupled to CRM197, the nontoxic mutant protein related to diphtheria toxin.

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The functionality of the antibody responses induced with immunogenic conjugates can be assessed. For example, functionality can be assessed by measuring the ability of the anti-PS antibody to opsonize encapsulated *S. pneumococcus* and lead to bacterial killing after phagocytosis by macrophages. Protection of animals from lethal challenge with *S. pneumococcus* is another way to

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demonstrate the efficacy of the immunogenic conjugate in immunized animals.

*Example 5: Combination of Immunogenic Conjugates with Adjuvants*

The PS-carrier protein immunogenic conjugate can be modified to further stimulate the immune response, and ultimately improve the efficacy of the immunization, by addition of an adjuvant. The immunogenic conjugate can be absorbed by an alum adjuvant such as aluminum hydroxide gel. Additionally, the immunogenic can be combined with an emulsion adjuvant such as squalene based oil in water nano emulsion. Adjuvants such as these can be used to create a delivery system for the immunogenic conjugate and function to create depots that trap the conjugated antigen-carrier protein at the site of injection to allow for its slow release. This allows for extended stimulation of the immune system by enabling the immunogenic conjugate to persist at the site of injection, increasing the recruitment and activation of immune cells.

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**OTHER EMBODIMENTS**

All publications and patents cited in this specification, as well as U.S. Provisional Application No. 62/191,028, are incorporated herein by reference as if each individual publication or patent were specifically and individually indicated to be incorporated by reference in its entirety.

Various modifications and variations of the described invention will be apparent to those skilled in the art without departing from the scope and spirit of the invention. Although the invention has been described in connection with specific embodiments, it should be understood that the invention as claimed should not be unduly limited to such specific embodiments. Indeed, various modifications of the

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described modes for carrying out the invention that are obvious to those skilled in the art are intended to be within the scope of the invention.

Other embodiments are in the claims.

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**CLAIMS**What is claimed is:

1. An immunogenic composition comprising a polysaccharide-sortase conjugate, wherein said polysaccharide is an antigen and said sortase is a carrier protein, and wherein said sortase is covalently linked to said polysaccharide antigen by a [linker comprising a](#) sortase recognition sequence.
2. An immunogenic composition comprising a polysaccharide-protein conjugate, said conjugate comprising a polysaccharide antigen and a carrier protein, wherein said polysaccharide antigen is covalently linked to said carrier protein by a [linker comprising a](#) sortase recognition sequence and a polyglycine motif present at the N-terminus of said carrier protein.
3. The immunogenic composition of claim 1 or 2, wherein said sortase is selected from the group consisting of sortase A, sortase B, sortase C, and sortase D.
4. The immunogenic composition of claim 3, wherein said sortase is sortase A, or a fragment thereof.
5. The immunogenic composition of claim 4, wherein said sortase A comprises the amino acid sequence of SEQ ID NO: 1.
6. The immunogenic composition of claim 5, wherein said sortase comprises an amino acid sequence that has at least 90% identity to the amino acid sequence of SEQ ID NO: 1.
7. The immunogenic composition of claim 6, wherein said sortase comprises an amino acid sequence that has at least 95% identity to the amino acid sequence of SEQ ID NO: 1.
8. The immunogenic composition of claim 7, wherein said sortase comprises an amino acid sequence that has at least 99% identity to the amino acid sequence of SEQ ID NO: 1.
9. The immunogenic composition of claim 3, wherein said sortase is sortase B, or a fragment thereof.
10. The immunogenic composition of claim 3, wherein said sortase is sortase C, or a fragment thereof.
11. The immunogenic composition of claim 3, wherein said sortase is sortase D, or a fragment thereof.
12. The immunogenic composition of any one of claims 1 to 11, wherein said sortase comprises at least one mutation
13. The immunogenic composition of any one of claims 1 to 12, wherein said sortase comprises a substitution.

14. The immunogenic composition of claim 1 or claim 2, wherein said sortase recognition sequence has the formula  $X_1PX_2X_3X_4$ , where  $X_1$ - $X_4$  are any amino acid.
15. The immunogenic composition of claim 14, wherein said sortase recognition sequence has the formula  $X_1PX_2X_3G$  for a sortase A substrate, where  $X_1$  is Leu, Ile, Val or Met,  $X_2$  is any amino acid, and  $X_3$  is Ser, Thr or Ala.
16. The immunogenic composition of claim 15, wherein the sortase recognition sequence is  $LPX_1TG$  for a sortase A substrate, where  $X_1$  is any amino acid.
17. The immunogenic composition of claim 14, wherein the sortase recognition sequence is  $NPX_1TX_2$  for a sortase B substrate, where  $X_1$  is Lys or Gln and  $X_2$  is Asn, Asp, or Gly.
18. The immunogenic composition of claim 14, wherein the sortase recognition sequence is  $LPX_1TX_2$  for a sortase C substrate, where  $X_1$  and  $X_2$  are any amino acid.
19. The immunogenic composition of claim 14, wherein the sortase recognition sequence is  $LPX_1TA$  for a sortase D substrate, where  $X_1$  is any amino acid.
20. The immunogenic composition of claim 14, wherein the sortase recognition sequence is  $LAX_1TG$  for a sortase D substrate, where  $X_1$  is any amino acid.
21. The immunogenic composition of claim 2, wherein the polyglycine motif comprises an amino acid sequence selected from the group consisting of GG, GGG, GGGG, and GGGGG.
22. The immunogenic composition of claim 21, wherein the polyglycine motif comprises the amino acid sequence GGGGG.
23. The immunogenic composition of any one of claims 1 to 22, wherein said [sortase recognition sequence is linked to said polysaccharide through  \$Z^1-C\(Z^2\)-N\(H\)-N\(H\)-\(-C\(O\)-\(L-C\(O\)\)\)\_n-N\(H\)-N\(H\)-m-Z^3\$](#)   
[wherein  \$Z^1\$  is a bond to an oxygen atom in said polysaccharide antigen,](#)  
 [\$Z^2\$  is a bond to a carbonyl group in said sortase recognition sequence,](#)  
 [\$Z^3\$  is O or NH,](#)  
[each of n and m is 0 or 1, and](#)  
[L, when present, is 02-6 alkanediyl or C6-io arenediyl.](#)
24. [The immunogenic composition of any one of claims 1 to 23, wherein said](#) carrier protein molecules are selected from the group consisting of diphtheria toxin, diphtheria toxoid, tetanus toxin, tetanus toxoid, *Pseudomonas aeruginosa* exotoxin A, cholera toxin B subunit, tetanus toxin fragment C, bacterial flagellin, pneumolysin, an outer membrane protein of *Neisseria meningitidis*, *Pseudomonas aeruginosa* Hcp1 protein, *Escherichia coli* heat labile enterotoxin, shiga-like toxin, human LTB protein, pneumolysin, listeriolysin O, a protein extract from whole bacterial cells, the dominant negative mutant (DNI) of the protective antigen of *Bacillus anthracis*, and *Escherichia coli* beta-galactosidase.

25. The immunogenic composition of claim 24, wherein said whole bacterial cells are *Pseudomonas aeruginosa* or *Streptococcal* cells.

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26. The immunogenic composition of claim 24, wherein said bacterial flagellin is the *Vibrio cholerae* flagellin protein.

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27. The immunogenic composition of claim 24, wherein said shiga-like toxin is the *Shigella* StxB2 protein.

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28. The immunogenic composition of claim 24, wherein said carrier protein molecules are pneumolysin.

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29. The immunogenic composition of claim 24, wherein said carrier protein molecules are listeriolysin O.

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30. The immunogenic composition of claim 24, wherein said carrier protein molecules are diphtheria toxin.

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31. The immunogenic composition of claim 24, wherein said carrier protein molecules are diphtheria toxoid.

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32. The immunogenic composition of claim 24, wherein said carrier protein molecules are tetanus toxin.

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33. The immunogenic composition of claim 24, wherein said carrier protein molecules are tetanus toxoid.

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34. The immunogenic composition of any one of claims 1 to 33, wherein said antigen of interest is a polysaccharide, a polyalcohol, or a poly amino acid.

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35. The immunogenic composition of claim 34, wherein said polysaccharide comprises at least 18 residues.

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36. The immunogenic composition of claim 34, wherein said polysaccharide is a *Streptococcus pneumoniae* polysaccharide, *Francisella tularensis* polysaccharide, *Bacillus anthracis* polysaccharide, *Haemophilus influenzae* polysaccharide, *Salmonella typhi* polysaccharide, *Salmonella* species polysaccharide, *Shigella* polysaccharide, or *Neisseria meningitidis* polysaccharide.

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37. The immunogenic composition of claim 34, wherein said *Streptococcus pneumoniae* polysaccharide is capsular type 1, 2, 3, 4, 5, 6A, 6B, 7A, 7B, 7C, 7F, 8, 9A, 9L, 9N, 9V, 10A, 10B, 10F, 11A, 11B, 11C, 11D, 11F, 12A, 12B, 12F, 13, 14, 15A, 15B, 15C, 15F, 16A, 16F, 17A, 17F, 18A, 18B, 18C, 18F, 19A, 19B, 19C, 19F, 20, 21, 22F, 23B, 23F, 24A, 24B, 24F, 25A, 25F, 27, 28A, 28F, 29, 31,

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32A, 32F, 33A, 33B, 33D, 33F, 34, 35A, 35B, 35F, 36, 37, 38, 39, 40, 41A, 41F, 42, 43, 44, 45, 46, 47A, 47F, or 48.

38. The immunogenic composition of claim 36, wherein said *Francisella tularensis* polysaccharide is 0 antigen.

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39. The immunogenic composition of any one of claims 34 to 38, wherein said antigen of interest is a microbial capsular polymer.

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40. The immunogenic composition of claim 39, wherein said microbial capsular polymer is poly-gamma-D-glutamic acid from *Bacillus anthracis*.

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41. The immunogenic composition of any one of claims 34 to 40, wherein said antigen of interest is an organic polymer consisting of monomers having at least three atoms, wherein each of said atoms is independently selected from the group consisting of carbon, oxygen, hydrogen, phosphate, nitrogen, and sulfate.

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42. The immunogenic composition of claim 41, wherein said organic polymer is obtained from a microbe.

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43. The immunogenic composition of claim 41, wherein said organic polymer does not occur in nature.

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44. The immunogenic composition of any one of claims 1 to 43, wherein said immunogenic composition further comprises a second antigen of interest.

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45. The immunogenic composition of any one of claims 1 to 44, wherein said immunogenic composition further comprises a third antigen of interest.

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46. The immunogenic composition of any one of claims 1 to 45, wherein said antigen of interest comprises whole cell pathogens.

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47. The immunogenic composition of claim 46, wherein said whole cell pathogens comprise heat inactivated whole cell pathogens.

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48. The immunogenic composition of claim 46, wherein said whole cell pathogens comprise chemically inactivated whole cell pathogens.

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49. The immunogenic composition of any one of claims 46 to 48, wherein said whole cell pathogens comprise *Pseudomonas aeruginosa* or *Streptococcal* cells.

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50. The immunogenic composition of claim 49, wherein said *Streptococcal* cells comprise *Streptococcus pneumoniae*.

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Deleted: 50. The immunogenic composition of claim 49, wherein said whole cell pathogens are *Streptococcus pneumoniae* type 1, 2, 3, 4, 5, 6A, 6B, 7A, 7B, 7C, 7F, 8, 9A, 9L, 9N, 9V, 10A, 10B, 10F, 11A, 11B, 11C,¶

51. The immunogenic composition of claim 50, wherein said whole cell pathogens are *Streptococcus pneumoniae* type 1, 2, 3, 4, 5, 6A, 6B, 7 A, 7B, 7C, 7F, 8, 9A, 9L, 9N, 9V, 10A, 10B, 10F, 11A, 11B, 11C, 11D, 11F, 12A, 12B, 12F, 13, 14, 15A, 15B, 15C, 15F, 16A, 16F, 17A, 17F, 18A, 18B, 18C, 18F, 19A, 19B, 19C, 19F, 20, 21, 22F, 23B, 23F, 24A, 24B, 24F, 25A, 25F, 27, 28A, 28F, 29, 31, 32A, 32F, 33A, 33B, 33D, 33F, 34, 35A, 35B, 35F, 36, 37, 38, 39, 40, 41A, 41F, 42, 43, 44, 45, 46, 47A, 47F, or 48.

52. The immunogenic composition of claim 51, wherein said antigen of interest comprises at least one whole cell pathogen selected from the group consisting of *Streptococcus pneumoniae* type 1, 2, 3, 4, 5, 6A, 6B, 7A, 7B, 7C, 7F, 8, 9A, 9L, 9N, 9V, 10A, 10B, 10F, 11A, 11B, 11C, 11D, 11F, 12A, 12B, 12F, 13, 14, 15A, 15B, 15C, 15F, 16A, 16F, 17A, 17F, 18A, 18B, 18C, 18F, 19A, 19B, 19C, 19F, 20, 21, 22F, 23B, 23F, 24A, 24B, 24F, 25A, 25F, 27, 28A, 28F, 29, 31, 32A, 32F, 33A, 33B, 33D, 33F, 34, 35A, 35B, 35F, 36, 37, 38, 39, 40, 41A, 41F, 42, 43, 44, 45, 46, 47A, 47F, and 48.

53. The immunogenic composition of claim 52, wherein said antigen of interest comprises two or more whole cell pathogens selected from the group consisting of *Streptococcus pneumoniae* type 1, 2, 3, 4, 5, 6A, 6B, 7A, 7B, 7C, 7F, 8, 9A, 9L, 9N, 9V, 10A, 10B, 10F, 11A, 11B, 11C, 11D, 11F, 12A, 12B, 12F, 13, 14, 15A, 15B, 15C, 15F, 16A, 16F, 17A, 17F, 18A, 18B, 18C, 18F, 19A, 19B, 19C, 19F, 20, 21, 22F, 23B, 23F, 24A, 24B, 24F, 25A, 25F, 27, 28A, 28F, 29, 31, 32A, 32F, 33A, 33B, 33D, 33F, 34, 35A, 35B, 35F, 36, 37, 38, 39, 40, 41A, 41 F, 42, 43, 44, 45, 46, 47A, 47F, and 48.

54. The immunogenic composition of any one of claims 1 to 53, wherein said complex, when administered to a mammal, elicits a T-cell dependent immune response in said mammal.

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55. The immunogenic composition of any one of claims 1 to 54, wherein the molar ratio of said antigen to said carrier protein molecules is 1 to 1.

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56. A pharmaceutical composition in unit dosage form comprising (i) the immunogenic composition of any one of claim 1 to 55 and (ii) a pharmaceutically acceptable excipient.

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57. The pharmaceutical composition of claim 56, wherein said pharmaceutical composition does not comprise an adjuvant.

58. A method of making an immunogenic composition of claim 1 or 2 comprising a polysaccharide-protein conjugate, said method comprising mixing a sortase and a polysaccharide antigen comprising a sortase recognition sequence, wherein said mixing results in formation of a thioester bond between said polysaccharide antigen and said sortase, yielding said polysaccharide-protein conjugate.

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59. The method of claim 58, said method further comprising mixing said polysaccharide-protein conjugate and a carrier protein comprising a polyglycine motif at its N-terminus, wherein said mixing results in formation of a peptide bond between a terminal carboxyl group of a sortase recognition

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sequence attached to said polysaccharide antigen and a terminal amino group of said polyglycine motif of said carrier protein.

60. The method of claim 58 or 59, wherein said polysaccharide antigen is a whole cell pathogen.

61. The method of claim 60, said method further comprising lysing said whole cell pathogen to produce a polysaccharide-protein conjugate, wherein said polysaccharide antigen in said polysaccharide-protein conjugate is not a whole cell pathogen.

62. The method of any one of claims 58 to 61, said method further comprising purifying said immunogenic composition.

63. The method of any one of claims 58 to 62, said method further comprising preparing said polysaccharide antigen comprising said sortase recognition sequence by mixing a polysaccharide cyanate with a hydrazine-activated sortase recognition sequence, thereby effecting an addition reaction of a hydrazine moiety in said hydrazine-activated sortase recognition sequence to a cyanate group in said polysaccharide cyanate.

64. A method of generating an immune response in a subject comprising administering the pharmaceutical composition of claim 57 to a subject, wherein said immunogenic composition elicits a T-cell dependent immune response in said subject.

65. The method of claim 64, wherein said subject is an infant, a child, or an adolescent.

66. The method of claim 64 or 65, wherein said pharmaceutical composition is administered to said subject parenterally.

67. The method of claim 64 or 65, wherein said pharmaceutical composition is administered to said subject orally.

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