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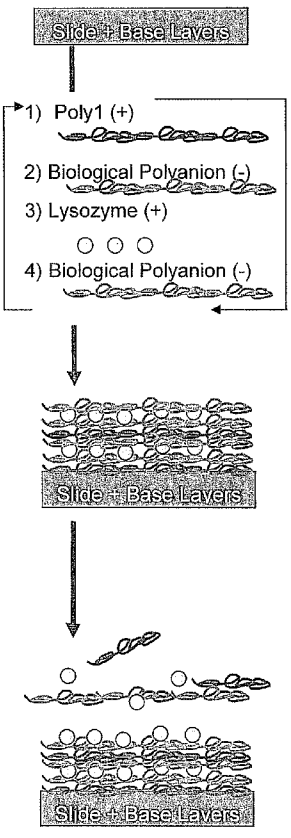


FIGURE 2

(57) Abstract: Provided are systems for controlled release of proteins from decomposable thin films constructed by layer-by-layer deposition. Such films generally comprise alternating layers of polymers and proteins, and may further comprise additional layers of polyions. In some embodiments, decomposable thin films and methods of using such films allow proteins to be released over an extended period of time and/or retention of as much as 100% of function of released protein.

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Self Assembled Films for Protein and Drug Delivery Applications

Related Applications

[0001] This application claims priority to and claims benefit of U.S. Provisional Application No. 60/943,983 filed June 14, 2007, the entire contents of which are herein incorporated by reference.

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[0002] The work described herein was supported, in part, by grants from the National Institutes of Health (1-R01-AG029601-01) and a National Science Foundation Graduate Research Fellowship to Mara Macdonald. The work described herein made use, in part, of MRSEC Shared Facilities supported by the National Science Foundation under Award Number DMR-0213282. The Government of the United States has certain rights in this invention.

Background

[0003] Many proteins are potentially useful in therapeutic drug applications. Nevertheless, controlled delivery of proteins remains a challenge, due in part to the fragile nature of some proteins (such as enzyme polypeptides) and the ability of proteins to diffuse. Sustained delivery of proteins while maintaining function is particularly desirable.

[0004] Layer-by-layer (LbL) absorption of oppositely charged polyelectrolytes on substrates can be used to fabricate thin multi-layer films for drug development. Nevertheless, LbL-based methods of delivering drugs were traditionally based on the formation of uniform films from which drug escapes via diffusion. Such diffusion-based release limits or eliminates the opportunity for controlled sequential delivery of drugs released from the surface to the surrounding medium. With such films, a typical diffusive, nonlinear drug release pattern is observed, and rarely is diffusion-controlled release from LbL films sustained for more than a few hours.

[0005] Because release time is impacted by the affinity of the drug for water, it is directly related to the hydrophobic nature of the drug, rather than an externally controlled parameter. Thus, releasing drugs by diffusion is not a useful strategy for all hydrophilic drugs, such as

proteins. Other methods allow encapsulation of proteins within a shell of LbL coats for release under significant pH (pH 8 or higher) or ionic strength changes, nevertheless, this is impractical for many medical applications, as such large deviations from physiological conditions would be often deadly. Also, processing methods for such films typically involve harsh solvents, in addition to acidic byproducts of degradation, which may destroy the protein intended to be delivered.

Summary

[0006] In various embodiments, the invention provided systems for controlled release of proteins while preserving protein function using LbL deposition to incorporate proteins into decomposable thin films.

[0007] In one aspect, the invention provides decomposable thin films for releasing proteins. Such decomposable thin films generally comprise a plurality of multilayer units comprising a first layer having a first charge and second layer having a second charge. At least a portion of the multilayers comprise a protein and decomposition of the thin film is characterized by sequential removal of at least a portion of the layers having the first charge and degradation of layers having the second charge, and by release of the protein from the corresponding layer. The decomposable thin film comprises at least one degradable polyelectrolyte layer, wherein the degradable polyelectrolyte is hydrolyzable. Erosion of the polyelectrolyte layer allows release of the protein.

[0008] In certain embodiments, the decomposable thin film comprises alternating cationic and anionic layers, and decomposition of the thin film is characterized by hydrolytic degradation of at least a portion of a layer (such as a cationic layer, an anionic layer, or both). In some embodiments of the invention, the decomposable thin film is comprised of tetralayer units, with each tetralayer having a structure such as, for example, (cationic degradable polymer/polyanion/cationic protein/polyanion). Other structures are also contemplated in the invention. The protein can be any of a number of proteins, for example, growth factors, clotting factors, enzyme polypeptides, *etc.*

[0009] In certain embodiments, proteins released from films of the invention can be released in a controlled manner, for example, with a linear release profile. Such films with linear release

profiles may be amenable to therapeutic drug applications. Dosing and release kinetics may be altered by altering one or more characteristics such as, for example, the degradable polymer used in film construction, the number of multilayers comprising the film, and/or the type of additional materials (such as polyanions) that are used in the construction of the films. Additional film properties such as anticoagulant activity or providing matrix material for cell proliferation can be chosen through the polyanion used. Examples of polyanions that can be used in accordance with the invention include charged polysaccharides such as heparin and chondroitin.

[0010] The thin film can be adapted or shaped and/or deposited onto substrates having certain shapes. This may facilitate making such films amenable for drug applications, such as, for example, those in which the films would be implanted into a patient's body. For example, the film may be constructed as a hollow shell, or deposited onto substrates having various shapes.

[0011] In another aspect, the invention provides methods of releasing proteins using decomposable thin films of the invention.

[0012] In certain embodiments, films and methods provided in the invention allow protein release over a period of at least 34 days and/or up to 80-100% retention of function of protein released from such films.

Definitions

[0013] "**Biomolecules**": The term "biomolecules", as used herein, refers to molecules (*e.g.*, proteins, amino acids, peptides, polynucleotides, nucleotides, carbohydrates, sugars, lipids, nucleoproteins, glycoproteins, lipoproteins, steroids, etc.) whether naturally-occurring or artificially created (*e.g.*, by synthetic or recombinant methods) that are commonly found in cells and tissues. Specific classes of biomolecules include, but are not limited to, enzymes, receptors, neurotransmitters, hormones, cytokines, cell response modifiers such as growth factors and chemotactic factors, antibodies, vaccines, haptens, toxins, interferons, ribozymes, anti-sense agents, plasmids, DNA, and RNA.

[0014] "**Biocompatible**": The term "biocompatible", as used herein is intended to describe materials that do not elicit a substantial detrimental response *in vivo*.

[0015] "**Biodegradable**": As used herein, "biodegradable" polymers are polymers that

degrade fully under physiological or endosomal conditions. In preferred embodiments, the polymers and biodegradation byproducts are biocompatible. Biodegradable polymers are not necessarily hydrolytically degradable and may require enzymatic action to fully degrade.

[0016] "**Degradation**": The phrase "degradation", as used herein, relates to the cleavage of a covalent polymer backbone. Full degradation of a polymer breaks the polymer down to monomeric species.

[0017] "**Endosomal conditions**": The phrase "endosomal conditions", as used herein, relates to the range of chemical (*e.g.*, pH, ionic strength) and biochemical (*e.g.*, enzyme concentrations) conditions likely to be encountered within endosomal vesicles. For most endosomal vesicles, the endosomal pH ranges from about 5.0 to 6.5.

[0018] "**Hydrolytically degradable**": As used herein, "hydrolytically degradable" polymers are polymers that degrade fully in the sole presence of water. In preferred embodiments, the polymers and hydrolytic degradation byproducts are biocompatible. As used herein, the term "non-hydrolytically degradable" refers to polymers that do not fully degrade in the sole presence of water.

[0019] "**Physiological conditions**": The phrase "physiological conditions", as used herein, relates to the range of chemical (*e.g.*, pH, ionic strength) and biochemical (*e.g.*, enzyme concentrations) conditions likely to be encountered in the intracellular and extracellular fluids of tissues. For most tissues, the physiological pH ranges from about 7.0 to 7.4.

[0020] "**Polyelectrolyte**" or "**polyion**": The terms "polyelectrolyte" or "polyion", as used herein, refer to a polymer which under some set of conditions (*e.g.*, physiological conditions) has a net positive or negative charge. Polycations have a net positive charge and polyanions have a net negative charge. The net charge of a given polyelectrolyte or polyion may depend on the surrounding chemical conditions, *e.g.*, on the pH.

[0021] "**Polynucleotide**", "**nucleic acid**", or "**oligonucleotide**": The terms "polynucleotide", "nucleic acid", or "oligonucleotide" refer to a polymer of nucleotides. The terms "polynucleotide", "nucleic acid", and "oligonucleotide", may be used interchangeably. Typically, a polynucleotide comprises at least three nucleotides. DNAs and RNAs are polynucleotides. The polymer may include natural nucleosides (*i.e.*, adenosine, thymidine, guanosine, cytidine, uridine, deoxyadenosine, deoxythymidine, deoxyguanosine, and deoxycytidine), nucleoside analogs (*e.g.,* 2-aminoadenosine, 2-thiothymidine, inosine, pyrrolo-

pyrimidine, 3-methyl adenosine, C5-propynylcytidine, C5-propynyluridine, C5-bromouridine, C5-fluorouridine, C5-iodouridine, C5-methylcytidine, 7-deazaadenosine, 7-deazaguanosine, 8-oxoadenosine, 8-oxoguanosine, O(6)-methylguanine, and 2-thiocytidine), chemically modified bases, biologically modified bases (*e.g.*, methylated bases), intercalated bases, modified sugars (*e.g.*, 2′-fluororibose, ribose, 2′-deoxyribose, arabinose, and hexose), or modified phosphate groups (*e.g.*, phosphorothioates and 5′-N-phosphoramidite linkages).

[0022] "**Polypeptide**", "**peptide**", or "**protein**": According to the present invention, a "polypeptide", "peptide", or "protein" comprises a string of at least three amino acids linked together by peptide bonds. The terms "polypeptide", "peptide", and "protein", may be used interchangeably. Peptide may refer to an individual peptide or a collection of peptides. Inventive peptides preferably contain only natural amino acids, although non-natural amino acids (*i.e.*, compounds that do not occur in nature but that can be incorporated into a polypeptide chain; see, for example, http://www.cco.caltech.edu/ ~dadgrp/Unnatstruct.gif, which displays structures of non-natural amino acids that have been successfully incorporated into functional ion channels) and/or amino acid analogs as are known in the art may alternatively be employed. Also, one or more of the amino acids in an inventive peptide may be modified, for example, by the addition of a chemical entity such as a carbohydrate group, a phosphate group, a farnesyl group, an isofarnesyl group, a fatty acid group, a linker for conjugation, functionalization, or other modification, *etc.* In a preferred embodiment, the modifications of the peptide lead to a more stable peptide (*e.g.*, greater half-life *in vivo*). These modifications may include cyclization of the peptide, the incorporation of D-amino acids, *etc.* None of the modifications should substantially interfere with the desired biological activity of the peptide. The phrase "**enzyme polypeptide**" refers to a polypeptide having enzymatic activity.

[0023] "**Polysaccharide**", "**carbohydrate**" or "**oligosaccharide**": The terms "polysaccharide", "carbohydrate", or "oligosaccharide" refer to a polymer of sugars. The terms "polysaccharide", "carbohydrate", and "oligosaccharide", may be used interchangeably. Typically, a polysaccharide comprises at least three sugars. The polymer may include natural sugars (*e.g.*, glucose, fructose, galactose, mannose, arabinose, ribose, and xylose) and/or modified sugars (*e.g.*, 2′-fluororibose, 2′-deoxyribose, and hexose).

[0024] "**Small molecule**": As used herein, the term "small molecule" is used to refer to molecules, whether naturally-occurring or artificially created (*e.g.*, via chemical synthesis), that

have a relatively low molecular weight. Typically, small molecules are monomeric and have a molecular weight of less than about 1500 g/mol. Preferred small molecules are biologically active in that they produce a local or systemic effect in animals, preferably mammals, more preferably humans. In certain preferred embodiments, the small molecule is a drug. Preferably, though not necessarily, the drug is one that has already been deemed safe and effective for use by the appropriate governmental agency or body. For example, drugs for human use listed by the FDA under 21 C.F.R. §§ 330.5, 331 through 361, and 440 through 460; drugs for veterinary use listed by the FDA under 21 C.F.R. §§ 500 through 589, incorporated herein by reference, are all considered acceptable for use in accordance with the present invention.

[0025] **"Bioactive agents"**: As used herein, "bioactive agents" is used to refer to compounds or entities that alter, inhibit, activate, or otherwise affect biological or chemical events. For example, bioactive agents may include, but are not limited to, anti-AIDS substances, anti-cancer substances, antibiotics, immunosuppressants, anti-viral substances, enzyme inhibitors, neurotoxins, opioids, hypnotics, anti-histamines, lubricants, tranquilizers, anti-convulsants, muscle relaxants and anti-Parkinson substances, anti-spasmodics and muscle contractants including channel blockers, miotics and anti-cholinergics, anti-glaucoma compounds, anti-parasite and/or anti-protozoal compounds, modulators of cell-extracellular matrix interactions including cell growth inhibitors and anti-adhesion molecules, vasodilating agents, inhibitors of DNA, RNA or protein synthesis, anti-hypertensives, analgesics, anti-pyretics, steroidal and non-steroidal anti-inflammatory agents, anti-angiogenic factors, anti-secretory factors, anticoagulants and/or antithrombotic agents, local anesthetics, ophthalmics, prostaglandins, anti-depressants, anti-psychotic substances, anti-emetics, and imaging agents. In certain embodiments, the bioactive agent is a drug.

[0026] A more complete listing of bioactive agents and specific drugs suitable for use in the present invention may be found in "Pharmaceutical Substances: Syntheses, Patents, Applications" by Axel Kleemann and Jurgen Engel, Thieme Medical Publishing, 1999; the "Merck Index: An Encyclopedia of Chemicals, Drugs, and Biologicals", Edited by Susan Budavari *et al.*, CRC Press, 1996, and the United States Pharmacopeia-25/National Formulary-20, published by the United States Pharmcopeial Convention, Inc., Rockville MD, 2001, all of which are incorporated herein by reference.

Acronyms

[0027] The following acronyms are used herein: "SPS" is poly(styrene sulfonate), "PAA" is poly(acrylic acid), "LPEI" is linear poly(ethylene imine), "PDAC" is poly(diallyl dimethyl ammonium chloride), "PAH" is poly(allylamine hydrochloride), and "PAZO" is the azobenzene functionalized polymer poly{1-[4-(3-carboxy-4-hydroxyphenylazo) benzensulfonamido]-1,2 -ethanediyl}.

Brief Description of the Figures

[0028] **Figure 1** depicts chemical structures of certain polymers used in accordance with the invention. Shown are the structures for polymer 1 (Poly1), heparin sulfate, chondroitin sulfate, and polymer 2 (Poly2). Note that Poly1 and Poly2 differ only by two methylene units in the backbone.

[0029] **Figure 2** illustrates a scheme that may be used to construct a film using a cationic polymer (Poly1) comprising a cationic protein (lysozyme). Layers of a biological polyanion are deposited between layers of Poly1 and layers of lysozyme onto a substrate such as a slide. Thus, the film is comprised of tetralayers, each tetralayer having the structure (Poly1/polyanion/ lysozyme/polyanion.)

[0030] **Figures 3A-D** show results from characterization studies of (Poly1/heparin/lysozyme/heparin) tetralayers. Films were characterized by UV-Vis spectroscopy, profilometry, and instant dissolution methods. The nnumber of tetralayers is plotted against the signal recorded at the point of construction. **(A)**: UV-Vs absorbance of films at 280 nm with signal correction at 320 nm. **(B)**: Profilometry measurements of films. **(C)**: Amounts of protein instantaneously release from films as measured by a BCA (bicinchoninic acid) assay. **(D)**: Overlay of the three measurement techniques to compare curves, showing agreement of all three methods in detecting the characteristics of film buildup. Each signal value is taken as a percetage of the signal at 80 tetralayers.

[0031] **Figures 4A-D** show results indicating that release is affected by temperature of release and the number of tetralayers. Time in days is plotted against total amount of protein released in μg. **(A)**: Replicate samples dipped with the architecture [(Poly1/heparin/lysozyme/heparin)$_{80}$] were released at room temperature and displayed a linear release curve. **(B)**: Films with the architecture [(Poly1/heparin/lysozyme/heparin)$_{50}$] were

released at 37 °C and displayed a continued linear release profile. **(C)**: Films comprised of various numbers of tetralayers were released in PBS. Bsth the amount of protein incorporated and the time to total release are increased with increasing numbers of tetralayers.

[0032] **Figures 5A-C** show results of characterization studies of Poly2-containing films. **(A)**: The number of (poly2/heparin/lysozyme/heparin) tetralayers is plotted against the signal recorded at that point of construction. Each signal value is taken as a percentage of the signal at 50 tetralayers. **(B)**: Comparison of Poly1 and Poly2 buildup curves. The number of (PolyX/heparin/lysozyme/heparin) tetralayers is plotted versus the total thickness of the film as measured by profilometry. **(C)**: When poly2 is layered in the architecture $[(\text{Poly2/heparin/lysozyme/heparin})_{50}]$ and protein is released at 37 °C, release of over 34 days is achieved, showing the tenability of this system in response to desired characteristics.

[0033] **Figure 6** shows results of characterization studies of chondroitin-containing films. **(A):** The number of (Poly1/chondroitin/lysozyme/chondroitin) tetralayers is plotted against the signal recorded at that point of construction. Each signal value is taken as a percentage of the signal at 50 tetralayers. **(B)**: Release curves of chondroitin-containing and heparin-containing films. **(C)**: Release curves of films comprising various numbers of tetralayers constructed with lysozyme and chondroitin.

[0034] **Figures 7A-B** shows results of assays to determine function of released protein. The total amount of protein detected using the Micro BCA Protein Kit (Piece Biotechnologies) was plotted with the total amount of functional protein detected using the kinetic functional lysozyme assay; both values were plotted versus time.

[0035] **Figure 8** shows effects of dipping temperature on protein incorporation. The dipping process was performed in a cold room at about 4 °C, and an identical experiment was performed at room temperature. Both experiments were released at room temperature to show the effct of dipping temperature on the amount of protein incorporated.

Detailed Description of Certain Embodiments

[0036] As mentioned above, the invention provides, in various embodiments, systems for releasing proteins (including those having therapeutic value) in a controlled manner, while retaining activity of the released protein. Control may be achieved over dose, release rate, and/or time span.

Decomposable films

[0037] Decomposition of the thin films of the invention is characterized by the substantially sequential degradation of at least a portion of the polyelectrolyte layers that make up the thin films. The degradation may be at least partially hydrolytic, at least partially enzymatic, at least partially thermal, and/or at least partially photolytic. In some embodiments, the thin films are about 1 nm and about 100 μm thick, for example, between about 1 nm and about 100 nm thick, between about 100 nm and about 1 μm thick, between about 1 μm and about 10 μm thick, or between about 10 μm and about 100 μm thick.

[0038] Films are generally comprised of alternating layers of surface erodible polyelectrolytes (such as degradable polymers) and ionic proteins. The film may be comprised of mutilayer units with alternating layers of opposite charge, such as alternating anionic and cationic layers. For example, a cationic polyelectrolyte may be layered next to an anionic protein layer, and the bilayer unit repeated to make the thin film. Alternatively, an anionic polyelectrolyte may be layered next to a cationic protein layer.

[0039] At least one of the layers in a multilayer unit includes a degradable polyelectrolyte. As an example, the film may be comprised of an at least partially degradeable polycationic layer and a layer of anionic protein. The thin film may be exposed to a degrading medium (*e.g.*, intracellular fluid), whereupon the polycationic layers degrade and the protein layers delaminate sequentially from the surface toward the substrate. Proteins are thus gradually and controllably released from the surface of the thin film.

[0040] It will be appreciated that the roles of the layers of the thin film can be reversed. In such embodiments, the polyanionic layers include a degradable polyanion and the polycationic layers may include, for example, a polycationic protein. Alternatively, both the polycationic and polyanionic layers may both include degradable polyelectrolytes.

[0041] The invention also provides thin films in which the protein has the same charge as the chosen surface erodible polyelectrolyte. One such embodiment of the invention is illustrated in Figure 2, in which a film is created by deposition of tetralayer units on a substrate via layer-by-layer assembly. The tetralayer units depicted in Figure 2 comprise a layer of a cationic polymer (Poly1), a layer of a biologically active polyanion, a layer of the protein of interest (lysozyme in the example shown), and another layer of biologically active polyanion. Degradation of the film

and controlled release of proteins form the surface of the thin film proceeds as described above, except that sequential removal of the intervening polyanionic layers also occurs.

[0042] Degradable polyelectrolytes and their degradation byproducts may be biocompatible so as to make the films amemable to use *in vivo*.

Assembly methods

[0043] In certain embodiments, the LBL assembly of films may involve a series of dip coating steps in which the substrate is dipped in alternating polycationic and polyanionic solutions. Additionally or alternatively, it will be appreciated that deposition of alternating polycationic and polyanionic layers may also be achieved by spray coating, brush coating, roll coating, spin casting, or combinations of any of these techniques.

[0044] In certain embodiments, multiple layers of oppositely charged polymers are deposited on a charged surface from aqueous baths in a highly controllable process. Proteins can be incorporated into individual layers of the film, affording the opportunity for exquisite control of loading and release from the film. There are several advantages to this technique, including mild aqueous processing conditions (which may allow preserveation of biomolecule function); nanometer-scale conformal coating of surfaces; and the flexibility to coat objects of any size, shape or surface chemistry, leading to versatility in design options.

Substrates for constructing films

[0045] A variety of materials can be used as substrates of the present invention such as, but not limited to, metals, *e.g.*, gold, silver, platinum, and aluminum; metal-coated materials; metal oxides; plastics; ceramics; silicon; glasses; mica; graphite; hydrogels; and polymers such as polyamides, polyphosphazenes, polypropylfumarates, polyethers, polyacetals, polycyanoacrylates, polyurethanes, polycarbonates, polyanhydrides, polyorthoesters, polyhydroxyacids, polyacrylates, ethylene vinyl acetate polymers and other cellulose acetates, polystyrenes, poly(vinyl chloride), poly(vinyl fluoride), poly(vinyl imidazole), poly(vinyl alcohol), poly(ethylene terephthalate), polyesters, polyureas, polypropylene, polymethacrylate, polyethylene, poly(ethylene oxide)s and chlorosulphonated polyolefins; and combinations thereof. For example, a substrate of one material may be coated with a second material, or two materials may be combined to form a composite.

[0046] It will be appreciated that materials with an inherently charged surface are particularly attractive substrates for LBL assembly of a thin film. Alternatively, a range of methods are known in the art that can be used to charge the surface of a material, including but not limited to plasma processing, corona processing, flame processing, and chemical processing, *e.g.*, etching, micro-contact printing, and chemical modification. For example, plastics can be used as substrates, particularly if they have been chemically modified to present polar or charged functional groups on the surface. Additionally or alternatively, substrates can be primed with specific polyelectrolyte bilayers such as, but not limited to, LPEI/SPS, PDAC/SPS, PAH/SPS, LPEI/PAA, PDAC/PAA, and PAH/PAA bilayers, that form readily on weakly charged surfaces and occasionally on neutral surfaces. It will be appreciated that primer layers provide a uniform surface layer for further LBL assembly and are therefore particularly well suited to applications that require the deposition of a uniform thin film on a substrate that includes a range of materials on its surface, *e.g.*, an implant (such as stent) or a complex tissue engineering construct.

[0047] The substrate geometry may be manipulated to deposit films having a variety of shapes. For example, films may be deposited on particles, tubes, or spheres to facilitate a more uniform release distribution. Films may be deposited on strands such as sutures to release factors such as analgesics or antibiotics at a surgical site; coiled strands may also serve as substrates. Alternatively, these films may be deposited onto capillary networks or tissue engineering constructs. For example, a thin film deposited on a three-dimensional tissue engineering construct may be used to attract cells to a newly implanted construct and then to promote specific metabolic or proliferative activity.

[0048] Methods of the invention may also be used to create three-dimensional microstructures. For example, the thin film may be deposited on a substrate that can be dissolved to leave a hollow shell of the thin film. Alternatively or additionaly, multi-layers may be deposited on substrates having regions that are more and less degradable. Degradation of the degradable portions leaves a three-dimensional microstructure. In a first step, the surface of a substrate is divided into regions in which LBL deposition of an inventive thin film is more or less favorable. In one embodiment, a pattern of self-assembled monolayers (SAMs) is deposited on a substrate surface by microcontact printing (see, for example, U.S. Patent No. 5,512,131 to Kumar *et al.*, see also Kumar *et al.*, *Langmuir* 10:1498, 1994; Jiang and Hammond, *Langmuir*, 16:8501, 2000; Clark *et al.*, *Supramolecular Science* 4:141, 1997; and Hammond and

Whitesides, *Macromolecules* 28:7569, 1995). In some embodiments, the substrate surface is neutral and the exposed surface of the deposited SAMs is polar or ionic (*i.e.*, charged). A variety of polymers with polar or ionic head groups are known in the art of self-assembled monolayers. In some embodiments, a uniform coating of a polymer is deposited on a substrate, and that coating is transformed into a patterned layer by means of photolithography. Other embodiments are also contemplated in which the substrate surface is selectively exposed to plasmas, various forms of electromagnetic radiation, or to electron beams. In yet other embodiments, the substrate may possess the desired surface characteristics by virtue of its inherent composition. For example, the substrate may be a composite in which different regions of the surface have differing compositions, and thus different affinities for the polyelectrolyte to be deposited.

[0049] In a second step, polyelectrolyte layers of alternating charge are deposited by LBL on receptive regions of the surface as described for a homogeneous surface above and selective regions in Jiang and Hammond, *Langmuir*, 16:8501, 2000; Clark *et al.*, *Supramolecular Science* 4:141, 1997; and Hammond and Whitesides, *Macromolecules* 28:7569, 1995. The surface is subsequently flooded with a non-degradable polymer and placed in a medium wherein at least a portion of the polyelectrolyte layers degrade, thereby creating a three-dimensional "tunnel-like" structure that reflects the pattern on the original surface (see Figure 9, step D). It will be appreciated that more complex microstructures could be created based on these simple principles (*e.g.*, by depositing SAMs with different electrostatic character in different regions of a substrate surface and/or by iterative additions of subsequent structures above the deposited non-degradable polymer).

Degradable polyelectrolytes

[0050] Any degradable polyelectrolyte can be used in a thin film of the present invention, including, but not limited to, hydrolytically degradable, biodegradable, thermally degradable, and photolytically degradable polyelectrolytes. Hydrolytically degradable polymers known in the art include for example, certain polyesters, polyanhydrides, polyorthoesters, polyphosphazenes, and polyphosphoesters. Biodegradable polymers known in the art, include, for example, certain polyhydroxyacids, polypropylfumerates, polycaprolactones, polyamides, poly(amino acids), polyacetals, polyethers, biodegradable polycyanoacrylates, biodegradable polyurethanes and polysaccharides. For example, specific biodegradable polymers that may be

used in the present invention include but are not limited to polylysine, poly(lactic acid) (PLA), poly(glycolic acid) (PGA), poly(caprolactone) (PCL), poly(lactide-co-glycolide) (PLG), poly(lactide-co-caprolactone) (PLC), and poly(glycolide-co-caprolactone) (PGC). Those skilled in the art will recognize that this is an exemplary, not comprehensive, list of biodegradable polymers. The properties of these and other polymers and methods for preparing them are further described in the art. See, for example, U.S. Patents Nos. 6,123,727; 5,804,178; 5,770,417; 5,736,372; 5,716,404 to Vacanti; 6,095,148; 5,837,752 to Shastri; 5,902,599 to Anseth; 5,696,175; 5,514,378; 5,512,600 to Mikos; 5,399,665 to Barrera; 5,019,379 to Domb; 5,010,167 to Ron; 4,806,621; 4,638,045 to Kohn; and 4,946,929 to d'Amore; see also Wang *et al.*, *J. Am. Chem. Soc.* 123:9480, 2001; Lim *et al.*, *J. Am. Chem. Soc.* 123:2460, 2001; Langer, *Acc. Chem. Res.* 33:94, 2000; Langer, *J. Control Release* 62:7, 1999; and Uhrich *et al.*, *Chem. Rev.* 99:3181, 1999. Of course, co-polymers, mixtures, and adducts of these polymers may also be employed.

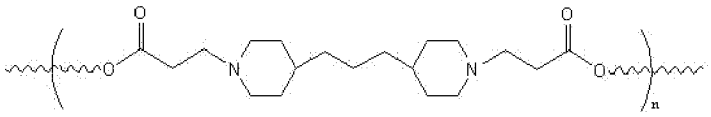
[0051] The anionic polyelectrolytes may be degradable polymers with anionic groups distributed along the polymer backbone. The anionic groups, which may include carboxylate, sulfonate, sulphate, phosphate, nitrate, or other negatively charged or ionizable groupings, may be disposed upon groups pendant from the backbone or may be incorporated in the backbone itself. The cationic polyelectrolytes may be degradable polymers with cationic groups distributed along the polymer backbone. The cationic groups, which may include protonated amine, quaternary ammonium or phosphonium-derived functions or other positively charged or ionizable groups, may be disposed in side groups pendant from the backbone, may be attached to the backbone directly, or can be incorporated in the backbone itself.

[0052] For example, a range of hydrolytically degradable amine containing polyesters bearing cationic side chains have recently been developed (Putnam *et al. Macromolecules* 32:3658-3662, 1999; Barrera *et al. J. Am. Chem. Soc.* 115:11010-11011, 1993; Kwon *et al. Macromolecules* 22:3250-3255, 1989; Lim *et al. J. Am. Chem. Soc.* 121:5633-5639, 1999; Zhou *et al. Macromolecules* 23:3399-3406, 1990; each of which is incorporated herein by reference). Examples of these polyesters include poly(L-lactide-co-L-lysine) (Barrera *et al. J. Am. Chem. Soc.* 115:11010-11011, 1993; incorporated herein by reference), poly(serine ester) (Zhou *et al. Macromolecules* 23:3399-3406, 1990; which is incorporated herein by reference), poly(4-hydroxy-L-proline ester) (Putnam *et al. Macromolecules* 32:3658-3662, 1999.; Lim *et al. J. Am.*

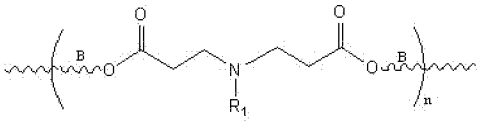
Chem. Soc. 121:5633-5639, 1999; each of which is incorporated herein by reference), and more recently, poly[α-(4-aminobutyl)-L-glycolic acid].

[0053] In addition, poly(β-amino ester)s, prepared from the conjugate addition of primary or secondary amines to diacrylates, are suitable for use with the invention. Typically, poly(β-amino ester)s have one or more tertiary amines in the backbone of the polymer, preferably one or two per repeating backbone unit. Alternatively, a co-polymer may be used in which one of the components is a poly(β-amino ester). Poly(β-amino ester)s are described in USSN 09/969,431, filed October 2, 2001, entitled "Biodegradable poly(β-amino esters) and uses thereof" and Lynn *et al.*, *J. Am. Chem. Soc.* 122:10761-10768, 2000, the entire contents of both of which are incorporated herein by reference.

[0054] Exemplary poly(β-amino ester)s include



and



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[0055] Exemplary R groups include hydrogen, branched and unbranched alkyl, branched and unbranched alkenyl, branched and unbranched alkynyl, aryl, halogen, hydroxyl, alkoxy, carbamoyl, carboxyl ester, carbonyldioxyl, amide, thiohydroxyl, alkylthioether, amino, alkylamino, dialkylamino, trialkylamino, cyano, ureido, a substituted alkanoyl group, cyclic, cyclic aromatic, heterocyclic, and aromatic heterocyclic groups, each of which may be substituted with at least one substituent selected from the group consisting of branched and unbranched alkyl, branched and unbranched alkenyl, branched and unbranched alkynyl, amino, alkylamino, dialkylamino, trialkylamino, aryl, ureido, heterocyclic, aromatic heterocyclic, cyclic, aromatic cyclic, halogen, hydroxyl, alkoxy, cyano, amide, carbamoyl, carboxylic acid, ester, carbonyl, carbonyldioxyl, alkylthioether, and thiol groups.

[0056] Exemplary linker groups A and B include carbon chains of 1 to 30 carbon atoms, heteroatom-containing carbon chains of 1 to 30 atoms, and carbon chains and heteroatom-containing carbon chains with at least one substituent selected from the group consisting of

branched and unbranched alkyl, branched and unbranched alkenyl, branched and unbranched alkynyl, amino, alkylamino, dialkylamino, trialkylamino, aryl, ureido, heterocyclic, aromatic heterocyclic, cyclic, aromatic cyclic, halogen, hydroxyl, alkoxy, cyano, amide, carbamoyl, carboxylic acid, ester, carbonyl, carbonyldioxyl, alkylthioether, and thiol groups. The polymer may include, for example, between 5 and 10,000 repeat units.

[0057] In some embodiments of the invention, the poly(β-amino ester) are Poly1 and/or Poly2 (whose structures are shown in Figure 1).

[0058] Alternatively or additionally, zwitterionic polyelectrolytes may be used. Such polyelectrolytes may have both anionic and cationic groups incorporated into the backbone or covalently attached to the backbone as part of a pendant group. Such polymers may be neutrally charged at one pH, positively charged at another pH, and negatively charged at a third pH. For example, a film may be deposited by LBL deposition using dip coating in solutions of a first pH at which one layer is anionic and a second layer is cationic. If the film is put into a solution having a second different pH, then the first layer may be rendered cationic while the second layer is rendered anionic, thereby changing the charges on those layers.

[0059] The composition of the polyanionic and polycationic layers can be fine-tuned to adjust the degradation rate of each layer within the film. For example, the degradation rate of hydrolytically degradable polyelectrolyte layers can be decreased by associating hydrophobic polymers such as hydrocarbons and lipids with one or more of the layers. Alternatively, the polyelectrolyte layers may be rendered more hydrophilic to increase their hydrolytic degradation rate. In certain embodiments, the degradation rate of a given layer can be adjusted by including a mixture of polyelectrolytes that degrade at different rates or under different conditions. In other embodiments, the polyanionic and/or polycationic layers may include a mixture of degradable and non-degradable polyelectrolytes. Any non-degradable polyelectrolyte can be used with the present invention. Exemplary non-degradable polyelectrolytes that could be used in thin films are shown in Figure 4 and include poly(styrene sulfonate) (SPS), poly(acrylic acid) (PAA), linear poly(ethylene imine) (LPEI), poly(diallyldimethyl ammonium chloride) (PDAC), and poly(allylamine hydrochloride) (PAH).

[0060] Alternatively or additionally, the degradation rate may be fine-tuned by associating or mixing non-biodegradable, yet biocompatible polymers (polyionic or non-polyionic) with one or more of the polyanionic and/or polycationic layers. Suitable non-biodegradable, yet

biocompatible polymers are well known in the art and include polystyrenes, certain polyesters, non-biodegradable polyurethanes, polyureas, poly(ethylene vinyl acetate), polypropylene, polymethacrylate, polyethylene, polycarbonates, and poly(ethylene oxide)s.

Proteins

[0061] Proteins that can be incorporated into films of the present invention include, but are not limited to, growth factors, clotting factors, and/or enzyme polypeptides. It may be desirable, for example, to release growth factors for tissue engineering purposes, and/or for implantable medical devices. Growth factors that may be released using films provided by the present invention include, but are not limited to, vascular endothelian growth factor (VEGF), bone morphogenic protein 2 (BMP-2), bone morphogenic protein 4 (BMP-4), and basic fibroblast growth factor.

[0062] Release of clotting factors (also known as coagulation factors) may promote desired biological processes such as wound healing in certain embodiments of the invention. The clotting factor may be, but is not limited to, factor I (fibrinogen), factor VII (prothrombin), factor III (tissue thromboplastin), factor V (proaccelerin), factor VII (proconvertin), factor VIII (antihemophilic factor), factor IX (plasma thromboplastin component), factor X (thrombokinase), factor XI (plasma thromboplastin antecedent), factor XII (Hageman factor), and factor XIII (fibrin stabilizing factor).

[0063] Enzymes other than some of the clotting factors listed above may also be released using films and methods of the present invention. For example, lysozyme lyse bacteria and may have therapeutic uses. Lysozyme is used as a model enzyme in Examples 3-8 in the present application. Example 8 demonstrates that enzyme released from films of the invention retain catalytic activity.

[0064] More than one protein can be released from a single film. For example, films may be constructed so as to have multiple layers of proteins (each layer containing different proteins), and/or such that the "protein layer" in each multilayer unit comprises more than one protein. This may be useful in applications, for example, that require or would benefit from release of more than one growth factor.

Polyions

[0065] Polyionic layers may be used in film construction and placed between protein layers and polyelectrolyte layers having the same charge. As discussed above, for example, in some embodiments, films comprise tetralayer units having the structure (degradable cationic polyelectrolyte/polyanion/cationic protein/polyanion). (Structures with reversed charge schemes, *e.g.*, comprising anionic polyelectrolytes, polycations, and anionic proteins, may also be possible with the present invention.)

[0066] Polyions used in accordance with the invention are generally biologically derived, though they need not be. Polyions that may be used in accordance with the invention include charged polysaccharides. This include glycosaminoglycans such as heparin, chondroitin, dermatan, hyaluronic acid, *etc.* (Some of these terms for glycoasminoglycans are often used interchangeably with the name of the sulfate form, *e.g.*, heparan sulfate, chondroitin sulfate, *etc.* It is intended that such sulfate forms are included among the list of polyions that may be used in accordance with the invention. Similarly, other derivatives or forms of such polysaccharides may be incorporated into films.)

[0067] In some embodiments, polyions also add characteristics to the film that are useful for medical applications. For example, heparin activates antithrombin III, which blocks thrombin activity, and therefore reduces clotting. Anti-clotting properties may be desirable for a delivery device or implant coating, as clotting as a serious concern with any device that may be put into contact with the bloodstream (*i.e.*, stents). Failure to address this concern may lead myocardial infarction, stroke, or ischemia of other vital organs.

[0068] In some applications, anticoagulation would be problematic (for example, at a wound site) and other characteristics would be desirable. For example, it may be desired to speed integration of an implanted device into surrounding host tissue. Providing an extracellular matrix-like environment that encourages cell proliferation may facilitate integration. In such cases, a polyion such as chondroitin (a native extracellular matrix component with anti-inflammatory properties) could be used.

Dose and release characteristics

[0069] As mentioned above, certain characteristics of degradable thin films of the invention may be modulated to achieve desired protein doses and/or release kinetics. Doses may be modulated, for example, by changing the number of multilayer units that make up the film, the

type of degradable polyelectrolyte used, the type of polyion (if any) used, and/or concentrations of protein solutions used during construction of the films. Similarly, release kinetics (both rate of release and duration of protein release) may be modulated by changing any or a combination of the aforementioned factors.

Methods

[0070] Also provided in the invention are methods of releasing a protein from a thin film of the invention. Such methods generally comprise steps of providing a decomposable thin film of the invention and placing the thin film in a medium in which at least a portion of the thin film decomposes via the substantially sequential removal of at least a portion of the layers having the first charge and degradation of layers having the second charge. The medium can be, for example, provided from *in vivo* environment such as a subject's body. In some embodiments, the medium can be provided in an artificial environment such as tissue engineering scaffold. Buffers such as phosphate-buffered saline may also serve as a suitable medium.

[0071] Release of protein may follow linear kinetics over a period of time. Such a release profile may be desirable to effect a particular dosing regimen. Certain embodiments of the invention provide systems for releasing proteins in a linear fashion over a period of at least 5, 10, or 14 days (see, for example, Figure 4A). Certain embodiments of the invention provide systems allowing protein release over a period of at least 5, 10, 15, 20, 25, 30, or 34 days (see, for example, Figure 5C).

[0072] Provided methods and systems allow release of functional proteins, such as discussed below in Example 8. In some embodiments, protein from thin films has at least 50%, 60%, 70%, 80%, and 90% activity (functional protein as compared to total protein) after being released from the films. In some embodiments, proteins released from thin films maintain up to as much 100% activity (see, for example, Figure 7.)

Examples

Example 1: Construction of decomposable protein-releasing films

[0073] In this Example, decomposable protein-releasing films were constructed by layer-by-layer deposition onto glass or quartz substrates. Biological polyanions were used between layers

of cationic polymers and layers of cationic protein, thus generating a tetralayer structure that was repeated to build the film.

Reagents and Solutions

[0074] Linear poly(ethylenimine) (LPEI, Mn = 25000) was obtained from Polysciences, Inc (Warrington, PA) and poly(sodium 4-styrenesulfonate) (PSS, Mn = 1000000) was obtained from Sigma-Aldrich (St. Louis, MO). Chondroitin sulfate sodium salt (Mn = 60000) was obtained from VWR Scientific (Edison, NJ) and heparin sodium salt was obtained from Celsus Laboratories (Cincinnati, OH). Poly 1 was synthesized as previously described[15]. Poly 2 was synthesized in a manner similar to that used to synthesize Poly 1. Lysozyme and *Micrococcus lysodeikticus* bacteria were obtained from Sigma Aldrich (St. Louis, MO). All commercial polyelectrolytes were used as received without further purification. A Micro BCA Protein Assay Kit was obtained from Pierce (Rockford, IL) and used according to manufacturer instructions. Glass and quartz slides (substrates) were obtained from VWR Scientific (Edison, NJ). Deionized water (18.2 MΩ, Milli-Q Ultrapure Water System, Millipore) was used for all washing steps. Dulbecco's PBS buffer was prepared from 10x concentrate available from Invitrogen (Frederick, MD).

Preparation of Polyelectrolyte Solutions

[0075] LPEI and PSS were dissolved in deionized water to a concentration of 10 mM with respect to repeat unit and pH adjusted to 4.25 and 4.75 respectively. Heparin, chondroitin, Poly 1, and Poly 2 were prepared in sodium acetate buffer (pH 5.1, 100 mM) at a concentration of 2 mg/mL. Lysozyme was prepared at a concentration of 0.5 mg/mL in 100 mM sodium acetate buffer, pH 5.1.

Film Construction

[0076] Glass substrates or quartz slides (1" x ¼") were rinsed with methanol and deionized water, dried under a stream of dry nitrogen, and plasma-etched in oxygen using a Harrick PDC-32G plasma cleaner on high RF power for 5 minutes. Ten base layers of (LPEI/PSS) were deposited upon plasma-etched substrates with a Carl Zeiss HSM series programmable slide stainer according to the following protocol: 5 minutes of dipping in LPEI, followed by three

washes (10, 20, and 30 s each) in deionized water, followed by 5 minutes in PSS and three deionized water washes (10, 20 and 30 s each) for 10 repetitions. On top of the base layers, tetralayers incorporating lysozyme were built with the following architecture: (Poly 1/heparin/ lysozyme/heparin)$_n$, where n refers to the number of tetralayers deposited on the substrate. A typical dipping protocol would be 10 minutes in a solution of Poly 1, 3 washes (10, 20, and 30 s each), 7.5 minutes in heparin with 3 washes (10, 20, and 30 s each), 10 minutes in the protein with 2 washes (20 and 30 s each) and 7.5 minutes in heparin with 3 washes (10, 20, and 30 s each). For the films characterized and used in Examples 2-6, Poly1 was dissolved in 100 mM sodium acetate buffer, pH 5.1. The protein used in the present Example (lysozyme) and the polyanion (heparin) were similarly dissolved in 100 mM sodium acetate buffer, pH 5.1. In the present Example, films were controlled to be approximately 0.75 inches x approximately 0.25 inches in size, or approximately 1.2 cm^2.

[0077] At the dipping conditions used (pH 5), Poly1 is cationic, and lysozyme was anticipated to be cationic as well (isoelectric point of 11). A four-layered repeat unit architecture with an anionic polymer (see Figure 2) in between Poly1 and lysozyme was used, allowing deposition of layers of opposite charges adjacent to one another. Films were thus comprised of tetralayers having the structure (Poly1/heparin/lysozyme/heparin).

Example 2: Characterization of protein-releasing films

[0078] In this Example, protein-releasing films constructed as described in Example 1 were characterized in terms of protein incorporation and growth.

Materials and methods

[0079] Varying numbers of tetralayers were deposited onto clean quartz substrates pre-treated with 10 base layers. Three techniques were used to analyze buildup. The thickness of the resulting films was measured by scoring the samples to the base of the film with a razor blade and measuring the step height using a profilometer (P10 Surface Profiler) with a 2 μm tip radius stylus. Protein incorporation in the film was measured by UV-Vis spectroscopy. A profile was taken of each sample on a Cary 6000i spectrophotometer from 200-800 nm. Proteins absorb at 280 nm due to tryptophan, tyrosine, and cysteine, and the intensity of absorption can then be correlated to protein buildup within the film. Absorbance values at 320 nm were measured as a

baseline value and was subtracted from absorbance values at 280 nm. Baseline-corrected absorbance values were plotted against number of tetralayers.

[0080] To quantify the total protein concentration in the film, constructed films were spontaneously dissolved using 1 mL of 1M NaOH for 1 hour, which disrupts film architecture and releases all incorporated drug. A 50 μL sample was quenched in 1X PBS and read using a Micro BCA Protein Assay Kit (Pierce Biotechnology, Rockford, IL). Bicinchoninic acid can be used to quantify protein concentration by detecting a reduction of copper by the protein of interest in an alkaline environment. A color change can be monitored and compared to a constructed standard curve. Triplicate 100 μL aliquots of standards and samples were run in 96 well plates according to the manufacturer's protocol and read on a microplate reader (PowerWave XS, BioTek, Winooski VT).

[0081] Using measurements from standard samples of known concentration, a standard curve of concentration versus slope was constructed for the concentration range 0-200 μg/mL. The standard curve was linear over this concentration range. Lysozyme concentrations of unknown samples were interpolated from the standard curve using the slopes for each sample. The error bars in Figures 3-7 represent a 99% confidence interval calculated from triplicate repeat samples of 2 independent trials (resulting in a total of 6 data points for each sample or standard.

Results and Discussion

[0082] Film buildup was tracked by monitoring thickness, protein incorporation, and instantaneous protein release (see Figure 3). After a brief induction period where little protein incorporation, film thickness, or protein release is achieved (approximately 10-20 tetralayers), all three methods indicate that the films build and incorporate protein in a roughly linear fashion (Figure 3 A-D).

[0083] An induction period for multilayer growth is typical of many LbL systems and has been reported in the literature[23,24]. It is believed, without being held to theory, that in this initial period, surface effects influence the buildup of the LbL film until complete surface coverage is achieved after several adsorption cycles. Furthermore, superlinear growth occurs as interdiffusion occurs within the layers of the film.

[0084] Protein content was measured by two techniques (UV-Vis, Figure 3A; BCA, Figure 3C), and total film buildup was measured by profilometry as described above (see Figure 3B).

Protein incorporation became linear after approximately 10 tetralayers, whereas thickness increase became linear at approximately 20 to 30 tetralayers. The thickness per tetralayer repeat unit in the linear growth regime is approximately 0.42 μm (420 nm), which is large in comparison with typical electrostatic multilayer systems that exhibit 10 to 100 nm per bilayer pair.

[0085] The disparity between the kinetics of protein incorporation and that of thickness suggests that although protein incorporation is substantially linear after just 10 tetralayers, the polymer composition in the film may be changing in a nonlinear fashion during this initial period. This regime of superlinear growth is hypothesized to be due to intermolecular interdiffusion of macromolecules into the film during the adsorption process, which leads to increasingly thick films[24,25] until the linear growth phase is reached.

[0086] It is believed, without being held to theory, that the linear characteristics of the second growth phase is created by a "front" in which interdiffusion of polymers into the bulk film remains possible. Such a front may vastly increase the amount of drug that can be incorporated in each dip step compared to the amount of drug that can be incoporated during initial steps (when the film and therefore the front are thinner). It is believed, without being held to theory, that underneath the front is a "reorganized" layer that is impermeable to diffusion, retaining the linearity of the film[23-25]. The diffusive character of the front and therefore of the film are affected by a number of factors including hydrophilicity of the polymer backbone, charge density of the polyions, and molecular weight of the polymers involved.

[0087] In general, there is strong agreement between the three measurement techniques, indicating excellent protein incorporation in the films, with linear build-up after an initial induction period (see Figure 3D). This linearity makes it simple to predict the additional amount of protein incorporated by adding subsequent tetralayers, as the amount incorporated increases linearly with the additional number of tetralayers dipped. For [Poly1/ heparin/ lysozyme/ heparin]$_{80}$ films, a UV-Vis signal of 2.064 units at 280 nm (Figure 1A) corresponded with a profilometry thickness of 23.7 μm (23780 nm) (Figure 1B), or approximately 1365 μg of loaded lysozyme.

Example 3: Characterization of protein release from films

[0088] In this Example, total protein released from films was determined as a function of

time.

Materials and Methods

[0089] Samples were released into phosphate buffered saline (pH 7.4) at either room temperature or 37 degrees Celsius in a microcentrifuge tube containing 1 mL of PBS. At a series of different time points, 0.5 mL of sample was removed and 0.5 mL of fresh PBS was introduced to the sample container. Samples were frozen at -20 °C until analyzed. Release of lysozyme into the solution was detected using the Micro BCA Protein Assay Kit as described in Example 2. For each time point analyzed, the total amount of protein released up to the time point was measured.

Results and Discussion

[0090] Proteins were released from films at 37 °C in PBS to approximate physiologic conditions and analyzed using a Micro BCA kit. As shown in Figure 4A (which depicts a release curve for 43 tetralayer-films), lysozyme is released with a linear trend over a period of approximately 14 days. Approximately 780 μg of incorporated protein (or 650 $\mu g/cm^2$) was released over the approximately 14-day time period.

[0091] The linear release trend may be desirable from multiple perspectives. This release trend may desirable for the drug delivery applications, because it allows constant, low levels of protein to be released from the surface. In burst release profiles, most of the protein is released instantly, consequently lost to a greater body volume, and cleared before therapeutic action can take place. In such burst release profiles, only a minority of drug is controlled in release. In contrast with burst release profiles, nearly all of the release from protein-releasing films of the invention occurs in a controlled, easy to predict (and therefore dose-oriented) fashion based on numbers of tetralayers used to build the film. Controlled delivery has significant advantages over pill or bolus injection methods, as it allows the concentration of the protein at the local site of interest to be kept within a therapeutic window between an upper limit of toxicity and a lower limit of effectiveness. In some embodiments, the invention therefore provides a new modality for the timed local release of proteins within the body where the expense or size of a dose was previously prohibitive. Loading more drug is possible by increasing the number of tetralayers in the film; it is also possible to predict the additional amount of protein incorporated.

[0092] In addition to these advantages, the controlled and linear release profile suggests a surface erosion mechanism for release. Previous studies of the degradation of poly(β-aminoester)-based LbL delivery indicated that degradation indeed occurs by surface-based erosion, based on AFM and similar measurements. The experiments described in this Example also illustrate that very large amounts of protein can be incorporated even in a mid-range number of tetralayers (films from 10 to 80 tetralayers were examined). Protein incorporation of up to approximately 1365 μg (or 1.14 mg/cm^2) is possible at 80 tetralayers in this particular Example (see Figure 3C). Most growth factor applications, by comparison, require only nanogram/mL concentrations of protein, suggesting that these films have a high upper limit loading capacity for such applications.

Example 4: Tuning of total dose and time scale of release by modifying the number of multilayer units

[0093] It can be envisioned that by tuning the number of tetralayers used in this system, it would be possible to change both the total dose administered as well as the time scale of release. Figure 4B depicts a family of release curves for films with (Poly 1/heparin/lysozyme/heparin)$_n$ architecture and varying numbers of tetralayers. As can be observed from Figure 4B, with increasing numbers of tetralayers, both the total amount of drug released and the time span of release are increased, consistent with the hypothesized mechanism of surface erosion. Films with 20 tetralayers released 100 μg of protein over 7 days, while films with 43 tetralayers released 780 μg of protein over 14 days. Bulk releasing films would possibly have increased loading with increasing numbers of tetralayers, but would release the entire load over the same amount of time, independent of the number of tetralayers. This characteristic of bulk releasing films, when taken together with the linear buildup and release of the film, supports the idea that a surface erosion mechanism of release (rather than a bulk diffusion mechanism) is responsible, as demonstrated and discussed in previous publications[2, 19].

[0094] Release studies also allowed for the calculation of the fraction of loaded films that is actually released. To address this question, two sets of films were constructed with the architecture (Poly1/heparin/lysozyme/heparin) and varying numbers of tetralayers. One set of films was released at 37 °C and the other was instantaneously released using a rapid deconstruction of the film, as described in the Materials and Methods section of Example 3. The

total release was calculated in each instance, and plotted in Figure 4C. Nearly 95% release or higher is observed at low numbers of tetralayers (50 tetralayers and below). At 80 tetralayers, approximately 85% release is achieved. Because this is a fully degradable system, it is anticipated that eventual recovery of the remaining 15% would occur over more extended time periods. Without being held to theory, it is hypothesized that the thickness of the film and incomplete degradation of overlying polymer networks hinders further release of protein from the film.

Example 5: Tuning of total dose and time scale of release by modifying the molecular structure of the polymer

[0095] One of advantage of using a synthetic erodible polymer is that the drug delivery from the device can be tuned through additional mechanisms over those already discussed by modifying the molecular structure of the polymer used. Poly1 is only one of a large family of poly(β-aminoesters) that can be used in these films; by tuning the composition of the polymers used for this purpose, one can alter the degradability of the ester bond and therefore decrease or increase the time scale over which the film degrades.

[0096] A second poly(β-aminoester), Poly2, was used to explore the effect of the kinetics of ester hydrolysis on drug release from the constructed multilayers (see Figure 1). Poly2 differs from Poly1 in that it has an additional two methylene units in the backbone next to the ester bond, making Poly2 more hydrophobic and making the ester bond less susceptible to hydrolysis. This decreased susceptibility to hydrolysis is predicted to decrease degradation and therefore increase time span of release. Thus, characterization and comparison between Poly1 and Poly2 films yields further interesting information on the erosion of these films as well as demonstrating that one can to tune release by tuning the characteristics of the synthetic polymer used.

[0097] Comparing buildup data of Poly2 compared to similar films for Poly1 (Figure 5A), there is similar agreement between the three measurement techniques, suggesting that linear film buildup and incorporation are first observed at 20 tetralayers. As an illustrative example, the profilometry data for P1 and P2 films have been plotted in Figure 5B to show the relative film buildup between the two compositions (100% in Figure 5A corresponds 50 tetralayer values: a UV-Vis reading of 1.52 absorbance units at 280 nm, a film thickness of approximately 13.23 μm, and protein incorporation of approximately 960 μg). In Figure 5B, a representative comparison

of profilometry measurements show that while both films exhibit similar growth trends, Poly2 incorporates more material at each measurement point. For example, at 50 tetralayers, Poly1 is able to incorporate approximately 780 μg of protein, whereas Poly2 is able to incorporate about 960 μg of protein.

[0098] The phenomenon of increasing drug loading with increasing hydrophobicity is well understood. It is believed, without being held to theory, that increasing hydrophobicity leads to a more "loopy" film architecture in which there are longer segments of polymer between electrostatic connections with the growing film and new polymer chains being incorporated. This increases both the film thickness and its ability to load more drug (by having a greater volume in which to pack drug). Hydrophobic interactions between the drug and the polymer may further enhance drug loading in these systems.

[0099] Figure 5C depicts amount of protein released over time from a film with the architecture $(Poly2/heparin/lysozyme/heparin)_n$. Over 34 days of release are observed with Poly2 films, indicating a 2x increase in release time using the more hydrophobic polymer. These results demonstrate that the time period of release can be modified by tuning the degradable polymer used. This data further supports the idea that surface erosion is the likely mechanism of release, as it is the hampered erosion of the ester bond that leads to increased release times.

Example 6: Tuning of total dose and time scale of release by using a different polyanion

[0100] Release behavior of the films can also be modified by incorporating a different polyanion, such as chondroitin. Chondroitin sulfate was incorporated in films of the architecture [Poly1/chondroitin/lysozyme/chondroitin] and varying numbers of tetralayers. Profilometry, UV-vis and instantaneous release curves are plotted and depicted in Figure 6A. Contrary to the film growth behavior for heparin, chondroitin buildup is characterized by a more extended period of time in the first, superlinear regime of the buildup process enabled by interdiffusion. Even by 50 tetralayers, it is unclear whether the films are beginning to build linearly or not; it is perhaps at this point that the films are just entering the second, linear regime of interdiffusion-based multilayer assembly. Film thickness values at 50 tetralayers are much lower than those of Poly 1/heparin or Poly 2/heparin films, suggesting that interdiffusion in these films may not be as extensive as that in films built with heparin. Without being held to theory, less extensive interdiffusion may explain the more extended period before entering the linear

interdiffusion/permeation controlled regime observed for chondroitin-containing films as compared to heparin-containing films. Protein incorporation is also lower than that of comparable heparin-based films. Table 1 summarizes UV-Vis absorbance at 280 nm (indicative of protein incorporated), thickness, and instantaneous protein release values for varying film constructions.

Table 1: Protein incorporation and thickness for films of varying constructions

Film construction	**UV-Vis absorbance**	**Thickness (μm)**	**Protein instantaneously released (μg)**
$(Poly1/chondroitin/lysozyme/chondroitin)_{50}$	0.24	2.73	160
$(Poly1/heparin/lysozyme/heparin)_{50}$	1.24	7.90	780
$(Poly2/heparin/lysozyme/heparin)_{50}$	1.52	13.23	960

[0101] Whereas linear incorporation was observed for heparin-containing films, superlinear incorporation was observed for chondroitin-containing films. Chondroitin-containing films showed an inverse exponential pattern of release, exhibiting a power law dependence with more lysozyme released first from the lysozyme-rich top layers of the film (see Figure 6B). The lower incorporation of lysozyme and faster time to completion of release of 3 to 4 days (see Figures 6B and 6C) are consistent with the overall thinner film and lower loading of protein. These films may be useful in applications in which a fairly sustainable burst at the beginning is desirable, with low levels of sustained release following. Shown in Figure 6C are release curves for chondroitin-containing films comprised of varying numbers of tetralayers. With increasing numbers of tetralayers, a trend of increased loading and time to complete release was observed, as had been seen with Poly1/heparin and Poly2/heparin films. The results in Figure 6B also show that total dose and release kinetics of chondroitin-containing films can be tuned.

Example 7: Activity of protein released from films

[0102] One concern in encapsulating proteins for drug delivery is whether the processing

conditions will destroy the activity of the encapsulated component. To quantify the functionality of released enzyme, activity assays of lysozyme were performed. Lysozyme's native activity is to cleave bacterial cell walls; one can detect the amount of functional lysozyme in solution by a kinetic reduction in turbidity of a bacterial solution.

Materials and Methods

[0103] Lysing of bacteria, such as can be achieved by lysozyme, will clear a cloudy suspension of bacteria; this clearing can be measured as a decrease in absorbance at 450 nm. Measurement was done as a kinetic plate reading assay. When absorbance at 450 nm is plotted against time, the slope of the graph is proportional to the concentration of lysozyme present in the solution.

[0104] Using measurements from standard samples of known concentration, a standard curve of concentration versus slope was constructed for the concentration range 0-200 μg/mL. The standard curve was linear over this concentration range. Functional lysozyme concentrations of unknown samples were interpolated from the standard curve using the slopes for each sample. In these tests, 290 μL of a 0.25 mg/mL solution of *Micrococcus lysodeikticus* was mixed with 10 μL of sample or standard. Each sample or standard was prepared in triplicate. Samples and standards were read in a 96 well plate at 450 nm every 15 seconds for a total of 10 readings. The readout from the assay is a concentration of lysozyme present based on the lysing ability of the sample, and thus represents the concentration of functional protein present in the sample.

Results and Discussion

[0105] In Figure 7, results of the micro-BCA assay for typical films are plotted in tandem with the results of a functional assay that reports the concentration of active enzyme present in a given sample. 80%-100% of activity is preserved within the films throughout the length of the trial. These rates of activity compare favorably with those of protein release from LbL films in the literature. In films described by Derbal *et al.*[26], activity at physiologic pH was possible, but long term activity of the enzyme (over a period of months) dropped to levels of approximately 30% of their original value. In capsules described by Caruso *et al.* and Tiourina *et al.* [9,10], excellent retention of activity was possible, ranging from 70 to 100%; however, the capsules required a high pH to release, which is unattainable for many medical device release

applications, and the system exhibited a burst style of release.

[0106] By combining hydrolytic degradability in a polyion directly with the protein of choice in LbL assembly, it is possible to protect and retain protein for long periods of time while sustaining the ability for extended release at biologically relevant conditions.

Example 8: Effect of dipping temperature on incorporated protein

[0107] Due to the fragile nature of many of the proteins that could potentially be used as drugs with films and methods of the present invention, the possibility of dipping at a reduced temperature in order to enhance protein stability during incorporation was explored. To lower the temperature of the dipping baths during the dipping process, the dipping apparatus was placed at 4 °C and the experiment run in a similar fashion to that of room temperature. As can be seen from Figure 8, the amount of incorporated protein decreases with decreased with dipping temperature but retains the general trends and characteristics during release of films dipped at room temperature.

[0108] Although lower amounts of protein are incorporated when dipping was performed at lower temperatures, lower dipping temperatures may be desirable in some embodiments, particularly with heat-sensitive proteins. Higher amounts of protein may be achieved with lower dipping temperatures by, for example, increasing the number of multilayers in the film and/or the concentration of protein in the adsorption baths.

[0109] All literature and similar material cited in this application, including, patents, patent applications, articles, books, treatises, dissertations and web pages, regardless of the format of such literature and similar materials, are expressly incorporated by reference in their entirety. In the event that one or more of the incorporated literature and similar materials differs from or contradicts this application, including defined terms, term usage, described techniques, or the like, this application controls.

[0110] The section headings used herein are for organizational purposes only and are not to be construed as limiting the subject matter described in any way.

Other embodiments and equivalents

[0111] While the present inventions have been described in conjunction with various embodiments and examples, it is not intended that the present inventions be limited to such embodiments or examples. On the contrary, the present inventions encompass various alternatives, modifications, and equivalents, as will be appreciated by those of skill in the art. Accordingly, the descriptions, methods and diagrams of should not be read as limited to the described order of elements unless stated to that effect.

[0112] Although this disclosure has described and illustrated certain embodiments of the invention, it is to be understood that the invention is not restricted to those particular embodiments. Rather, the invention includes all embodiments that are functional and/or equivalents of the specific embodiments and features that have been described and illustrated.

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Claims

We claim:

1. A decomposable thin film comprising:

a plurality of multilayer units comprising a first layer having a first charge and a second layer having a second charge, wherein:

at least a portion of the multilayers comprise a protein,

decomposition of the thin film is characterized by sequential removal of at least a portion of the layers having the first charge and degradation of layers having the second charge and by release of the protein from the corresponding layer, and

the decomposable thin film comprises at least one degradable polyelectrolyte layer, wherein the degradable polyelectrolyte is hydrolyzable.

2. The decomposable thin film of claim 1, wherein:

the thin film comprises alternating cationic and anionic layers, and

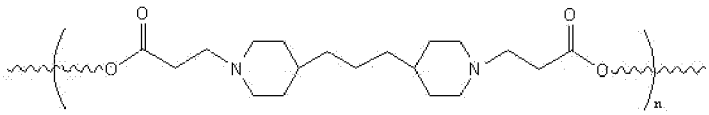
decomposition of the thin film is characterized by hydrolytic degradation of at least a portion of a layer selected from the group consisting of the cationic layers, the anionic layers, and both.

3. The decomposable thin film of claim 1, wherein at least a portion of the degradable polyelectrolyte layers comprises a polyelectrolyte selected from the group consisting of a synthetic polyelectrolyte, a natural polyelectrolyte, and both.

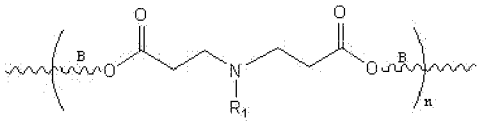
4. The decomposable thin film of claim 1, wherein at least a portion of the degradable polyelectrolyte layers comprises a polymer selected from polyesters, polyanhydrides, polyorthoesters, polyphosphazenes, polyphosphoesters, and combinations thereof.

5. The decomposable thin film of claim 4, wherein the polymer is a polyester selected from the group consisting of poly(β-amino ester)s, poly(L-lactide-co-L-lysine), poly(serine ester), poly(4-hydroxy-L-proline ester), poly[-(4-aminobutyl)-L-glycolic acid], and any combination thereof.

6. The decomposable thin film of claim 5, wherein the polyester is a poly(β-amino ester) selected from the group consisting of



and



wherein:

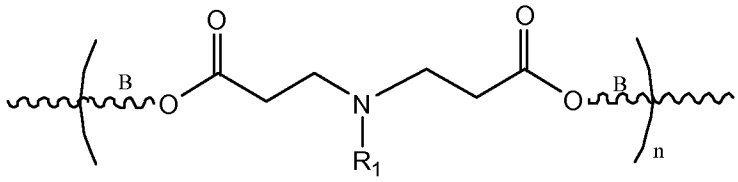
linker A and linker B are each independently selected from the group consisting of carbon chains of 1 to 30 carbon atoms, heteroatom-containing carbon chains of 1 to 30 atoms, and carbon chains and heteroatom-containing carbon chains with at least one substituent selected from the group consisting of branched and unbranched alkyl, branched and unbranched alkenyl, branched and unbranched alkynyl, amino, alkylamino, dialkylamino, trialkylamino, aryl, ureido, heterocyclic, aromatic heterocyclic, cyclic, aromatic cyclic, halogen, hydroxyl, alkoxy, cyano, amide, carbamoyl, carboxylic acid, ester, carbonyl, carbonyldioxyl, alkylthioether, and thiol groups;

R_1 and R_2 are each independently selected from the group consisting of hydrogen, branched and unbranched alkyl, branched and unbranched alkenyl, branched and unbranched alkynyl, aryl, halogen, hydroxyl, alkoxy, carbamoyl, carboxyl ester, carbonyldioxyl, amide, thiohydroxyl, alkylthioether, amino, alkylamino, dialkylamino, trialkylamino, cyano, ureido, a substituted alkanoyl group, cyclic, cyclic aromatic, heterocyclic, and aromatic heterocyclic groups, each of which may be substituted with at least one substituent selected from the group consisting of branched and unbranched alkyl, branched and unbranched alkenyl, branched and unbranched alkynyl, amino, alkylamino,

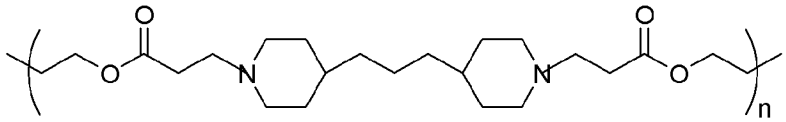
dialkylamino, trialkylamino, aryl, ureido, heterocyclic, aromatic heterocyclic, cyclic, aromatic cyclic, halogen, hydroxyl, alkoxy, cyano, amide, carbamoyl, carboxylic acid, ester, carbonyl, carbonyldioxyl, alkylthioether, and thiol groups; and

n is an integer greater than or equal to 5.

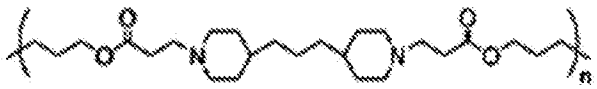
7. The decomposable thin film of claim 6, wherein the poly(β-amino ester) is



8. The decomposable thin film of claim 7, wherein the poly(β-amino ester) is



9. The decomposable thin film of claim 7, wherein the poly(β-amino ester) is



10. The decomposable thin film of claim 1, wherein at least a portion of the degradable polyelectrolyte layers comprises a polymer selected from poly(styrene sulfonate), poly(acrylic acid), linear poly(ethylene imine), poly(diallyl dimethyl ammonium chloride), poly(allylamine hydrochloride), and combinations thereof.
11. The decomposable thin film of claim 1, wherein the degradation is characterized by at least one characteristic selected from the group consisting of hydrolytic, thermal, enzymatic, and photolytic.
12. The decomposable thin film of claim 1, wherein at least a portion of the degradable polyelectrolyte layers comprises a biodegradable polymer.

13. The decomposable thin film of claim 12, wherein the biodegradable polymer is selected from polyhydroxyacids; polypropylfumerates; polycaprolactones; polyamides; poly(amino acids); polyacetals; polyethers; biodegradable polycyanoacrylates; biodegradable polyurethanes; polysaccharides; and co-polymers, mixtures, and adducts thereof.
14. The decomposable thin film of claim 1, wherein the thin film is adapted and constructed as a hollow shell.
15. The decomposable thin film of claim 1, wherein the thin film is deposited on a non-planar substrate.
16. The decomposable thin film of claim 15, wherein the thin film is deposited on a substrate having a shape selected from particles, tube, sphere, strand, coiled strand, and capillary network.
17. The decomposable thin film of claim 15, wherein degradation of the thin film enables dissolution of the substrate material.
18. The decomposable thin film of claim 15, wherein the substrate comprises a drug.
19. The decomposable thin film of claim 1, wherein the thin film is disposed on a substrate, wherein the surface properties of the substrate vary across a surface of the substrate.
20. The decomposable thin film of claim 1, wherein the thin film is disposed on a substrate comprising a material selected from metals, metal oxides, plastics, ceramics, silicon, glasses, mica, graphite, hydrogels, polymers, and any combination thereof.
21. The decomposable thin film of claim 1, wherein the protein is a growth factor.
22. The decomposable thin film of claim 21, wherein the growth factor is selected from the group consisting of vascular endothelial growth factor (VEGF), bone morphogenic protein 2 (BMP-2), bone morphogenic protein 4 (BMP-4), and basic fibroblast growth factor (bFGF).
23. The decomposable thin film of claim 1, wherein the protein is a clotting factor.
24. The decomposable thin film of claim 23, wherein the clotting factor is selected from the group consisting of factor I (fibrinogen), factor II (prothrombin), factor III (tissue thromboplastin), factor V (proaccelerin), factor VII (stable factor), factor VIII (antihemophilic fctor), factor IX (plasma thromboplastin component), factor X

(thrombokinase), factor XI (plasma thromobplastin antecedent), factor XII (Hageman factor), and factor XIII (fibrin stabilizing factor).

25. The decomposable thin film of claim 1, wherein the protein is an enzyme polypeptide.

26. The decomposable thin film of claim 25, wherein the enzyme polypeptide is lysozyme.

27. The decomposable thin film of claim 1, wherein the multilayer units comprise bilayer units of the structure (polyelectrolyte layer having the first charge/protein layer having the second charge).

28. The decomposable thin film of claim 1, wherein

the multilayer units each further comprise two layers, each layer having either the first charge or the second charge; and

each layer within the multilayer unit is adjacent to a layer having a different charge.

29. The decomposable thin film of claim 28, wherein the multilayer units comprise tetralayer units of the structure (polyelectrolyte having the first charge/first biopolymer having the second charge/ protein layer having the first charge/second biopolymer having the second charge).

30. The decomposable thin film of claim 29, wherein the first biopolymer and the second biopolymer are the same.

31. The decomposable thin film of claim 29, wherein at least one of the biopolymers is a polysaccharide.

32. The decomposable thin film of claim 31, wherein the polysaccharide is selected from the group consisting of heparan sulfate, chondroitin sulfate, hyaluronic acid, and dextran sulfate.

33. The decomposable thin film of claim 1, wherein the film comprises at least 10 multilayer units.

34. The decomposable thin film of claim 33, wherein the film comprises at least 20 multilayer units.

35. The decomposable thin film of claim 34, wherein the film comprises at least 30 multilayer units.

36. The decomposable thin film of claim 35, wherein the film comprises at least 40 multilayer units.

37. The decomposable thin film of claim 36, wherein the film comprises at least 50 multilayer units.

38. The decomposable thin film of claim 37, wherein the film comprises at least 60 multilayer units.

39. The decomposable thin film of claim 38, wherein the film comprises at least 70 multilayer units.

40. The decomposable thin film of claim 39, wherein the film comprises at least 80 multilayer units.

41. A method of releasing a protein from a thin film comprising:

providing a decomposable thin film comprising a plurality of multilayers including a first layer having a first charge and a second layer having a second change, wherein the protein is associated with at least one of the layers and the decomposable thin film includes at least one degradable polyelectrolyte layer, wherein the degradable polyelectrolyte is hydrolyzable; and

placing the thin film in a medium in which at least a portion of the thin film decomposes via the substantially sequential removal of at least a portion of the layers having the first charge and degradation of layers having the second charge.

42. The method of claim 41, wherein the protein is released from the thin film with linear kinetics over a period of at least 5 days.

43. The method of claim 41, wherein the protein is released from the thin film with linear kinetics over a period of at least 10 days.

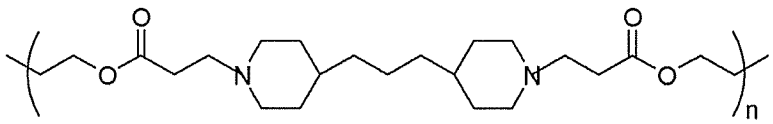
44. The method of claim 41, wherein the protein is released from the thin film with linear kinetics over a period of at least 14 days.

45. The method of claim 41, wherein the protein continues to be released from the thin film over a period of at least 5 days.

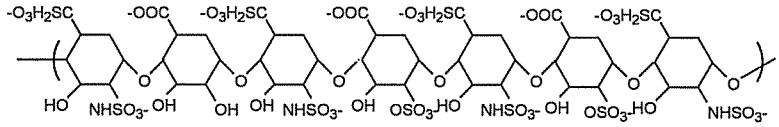
46. The method of claim 45, wherein the protein continues to be released from the thin film over a period of at least 10 days.

47. The method of claim 46, wherein the protein continues to be released from the thin film over a period of at least 15 days.

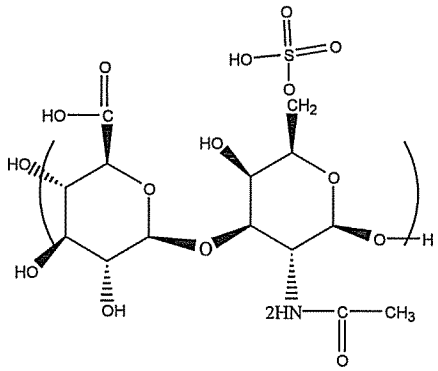
48. The method of claim 47, wherein the protein continues to be released from the thin film over a period of at least 20 days.
49. The method of claim 48, wherein the protein continues to be released from the thin film over a period of at least 25 days.
50. The method of claim 49, wherein the protein continues to be released from the thin film over a period of at least 30 days.
51. The method of claim 50, wherein the protein continues to be released from the thin film over a period of at least 34 days.
52. The method of claim 41, wherein protein released from the thin film has at least 50% activity after release from the thin film.
53. The method of claim 52, wherein protein released from the thin film has at least 60% activity after release from the thin film.
54. The method of claim 53, wherein protein released from the thin film has at least 70% activity after release from the thin film.
55. The method of claim 54, wherein protein released from the thin film has at least 80% activity after release from the thin film.
56. The method of claim 55, wherein the protein released from the thin film has at least 90% activity after release from the thin film.



Polymer 1 (Poly1)



Heparin Sulfate



Chondroitin Sulfate



Polymer 2 (Poly2)

FIGURE 1

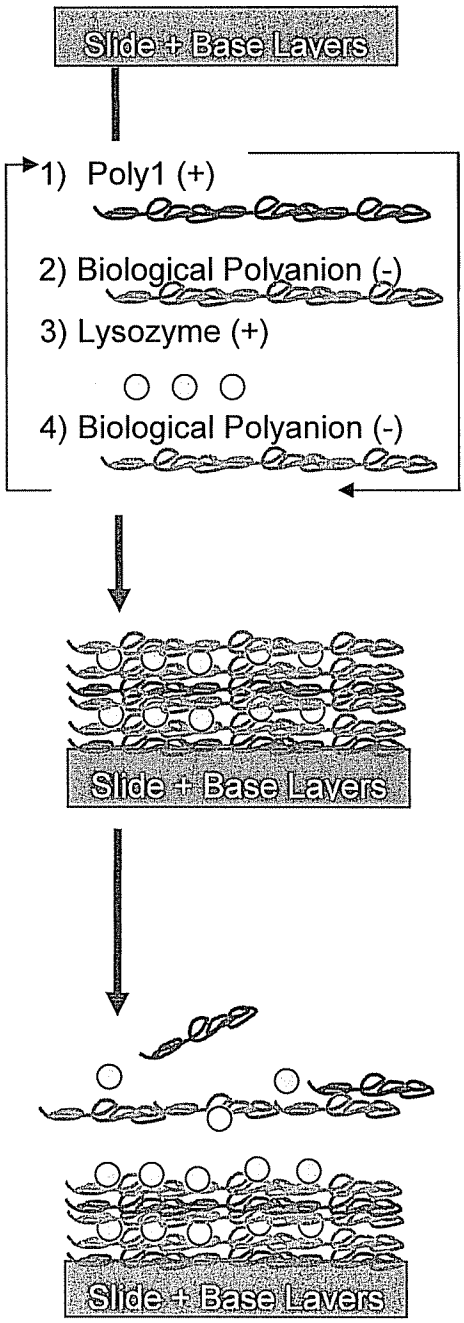
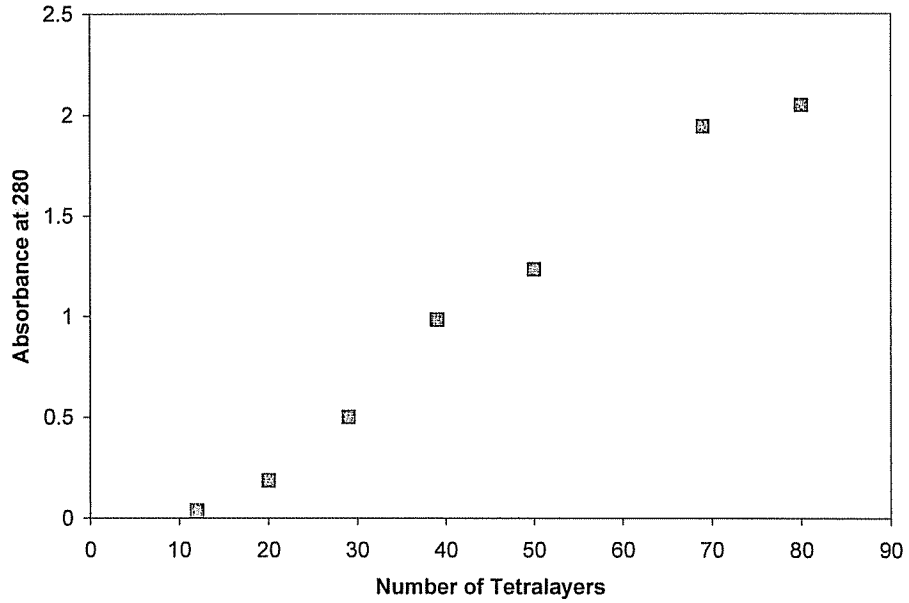
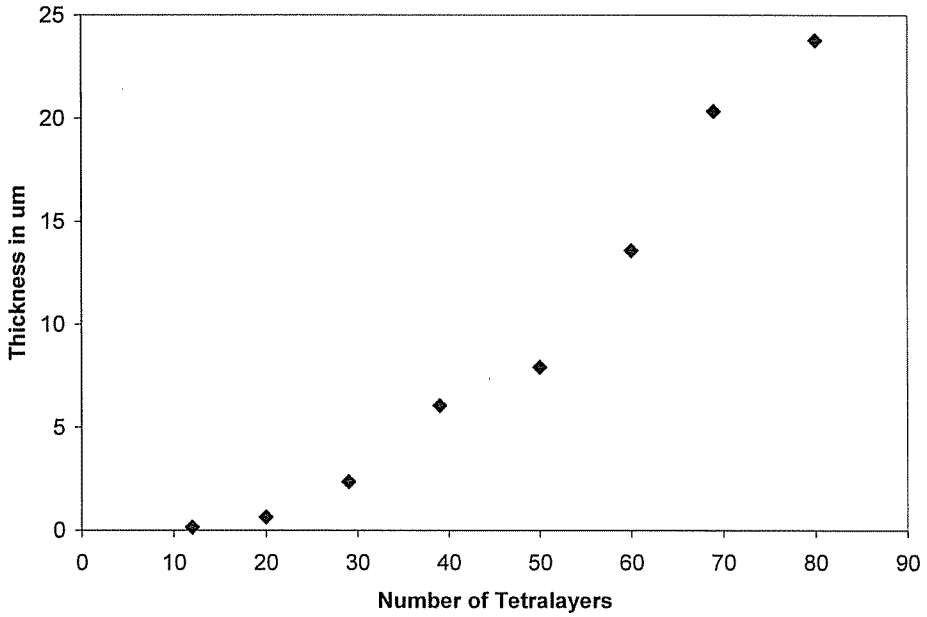

Slide + Base Layers
1) Poly1 (+)
2) Biological Polyanion (-)
3) Lysozyme (+)
4) Biological Polyanion (-)
Slide + Base Layers
Slide + Base Layers

FIGURE 2

A

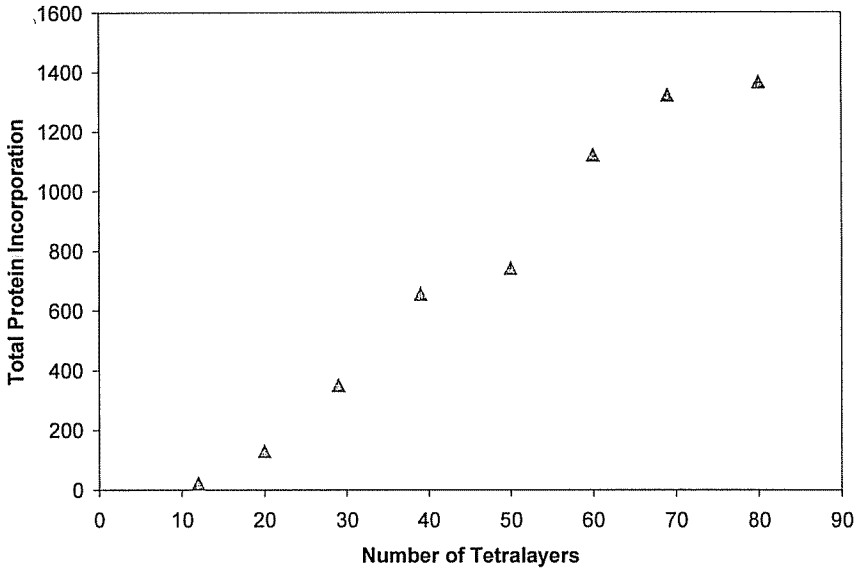


B

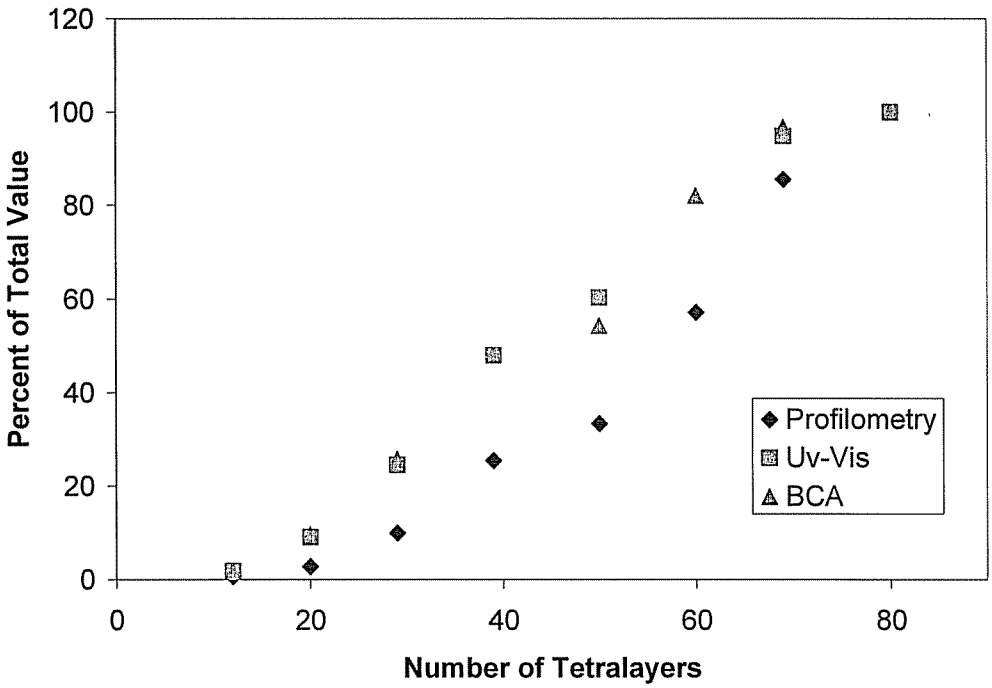


FIGURES 3A-B

C

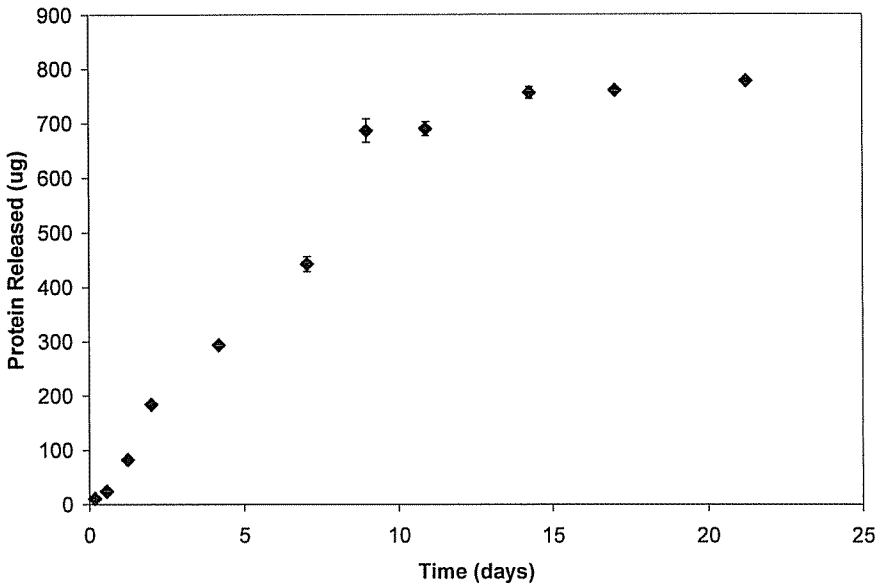


D

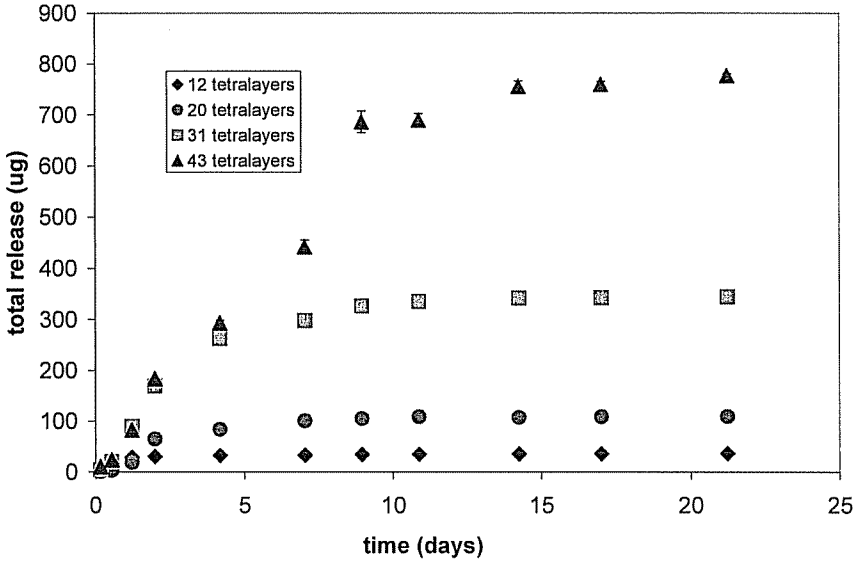


FIGURES 3C-D

A



B



FIGURES 4A-B

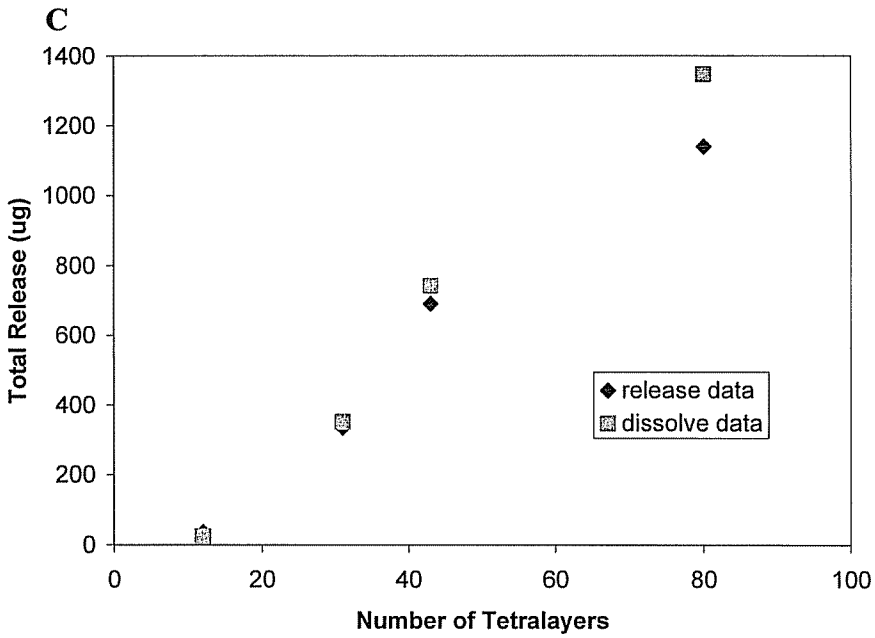
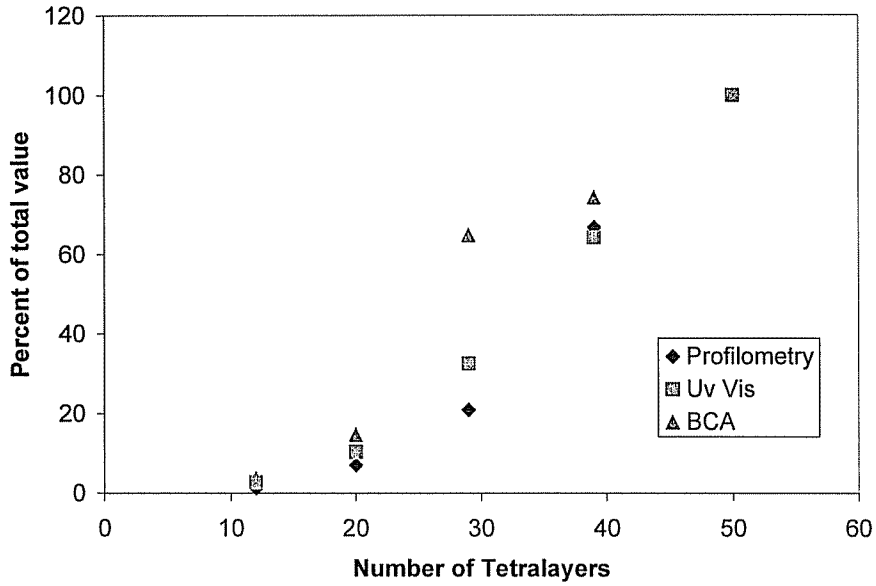
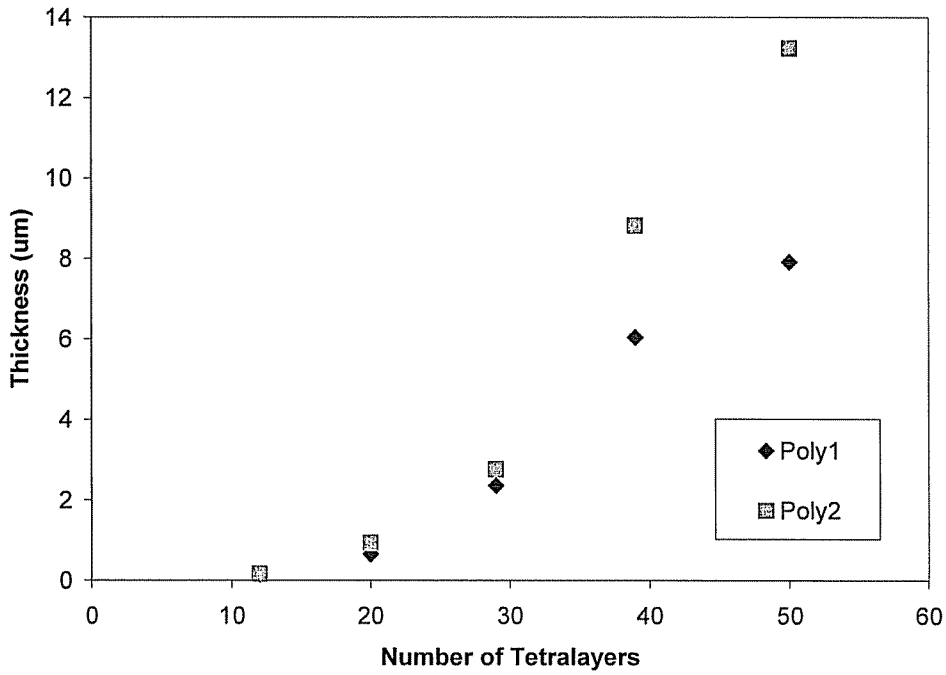

C
1400
1200
1000
800
600
400
200
0
Total Release (ug)
0
20
40
60
80
100
Number of Tetralayers
release data
dissolve data

FIGURE 4C

A



B



FIGURES 5A-B

C

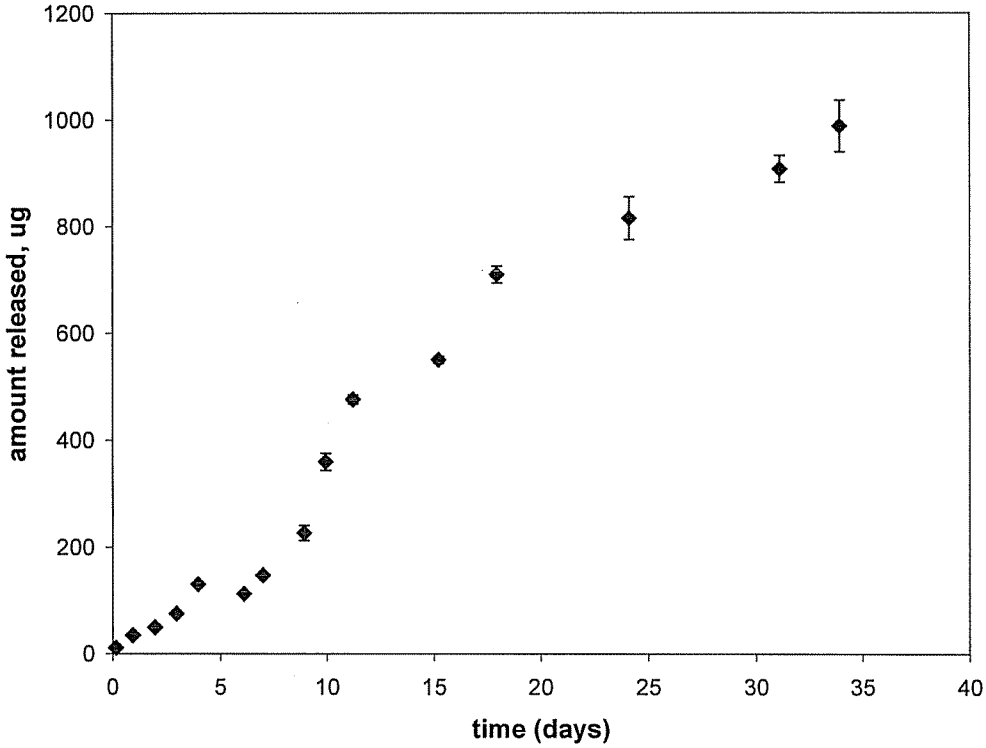
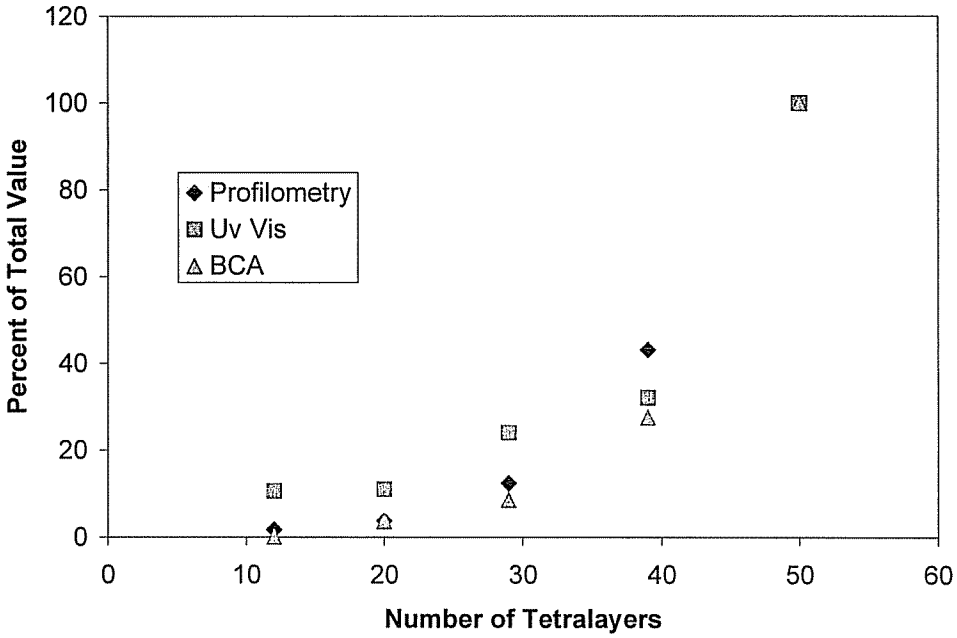
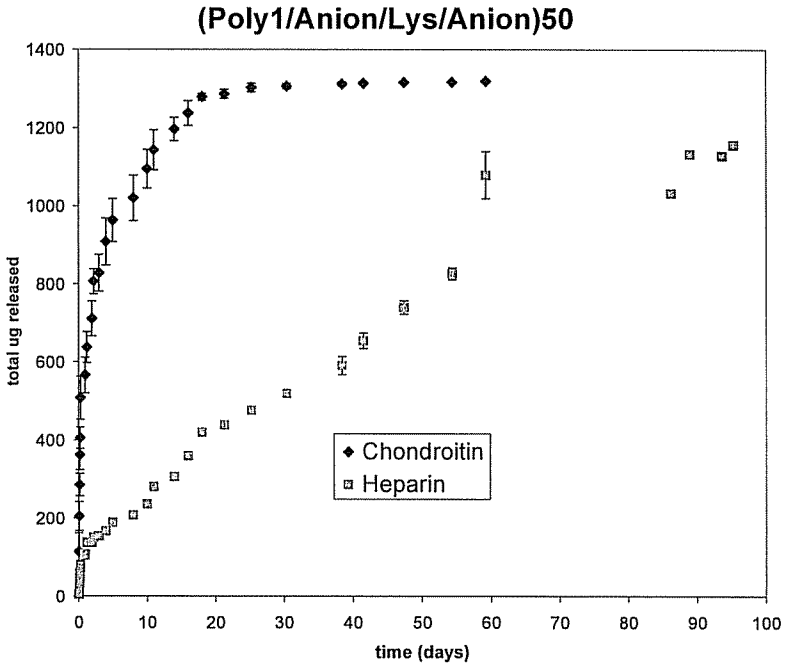

1200
1000
800
600
400
200
0
amount released, ug
0
5
10
15
20
25
30
35
40
time (days)

FIGURE 5C

A



B



FIGURES 6A-6B

C

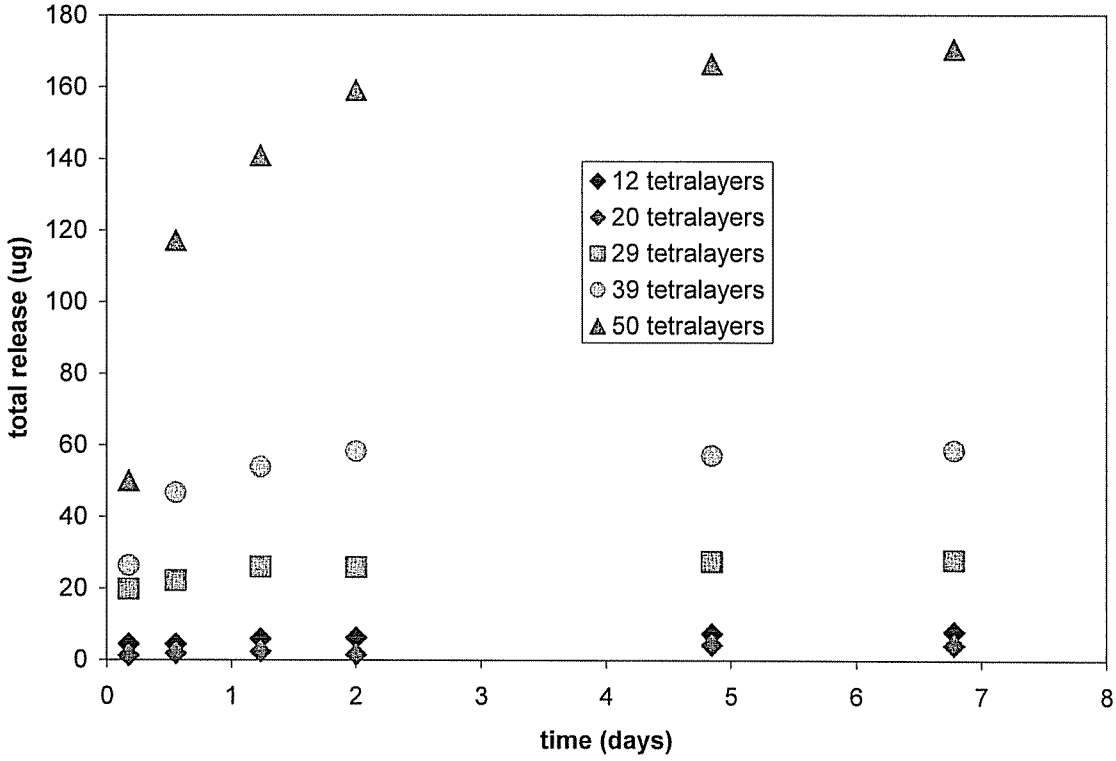

total release (ug)
time (days)
12 tetralayers
20 tetralayers
29 tetralayers
39 tetralayers
50 tetralayers
0
20
40
60
80
100
120
140
160
180
0
1
2
3
4
5
6
7
8

FIGURE 6C

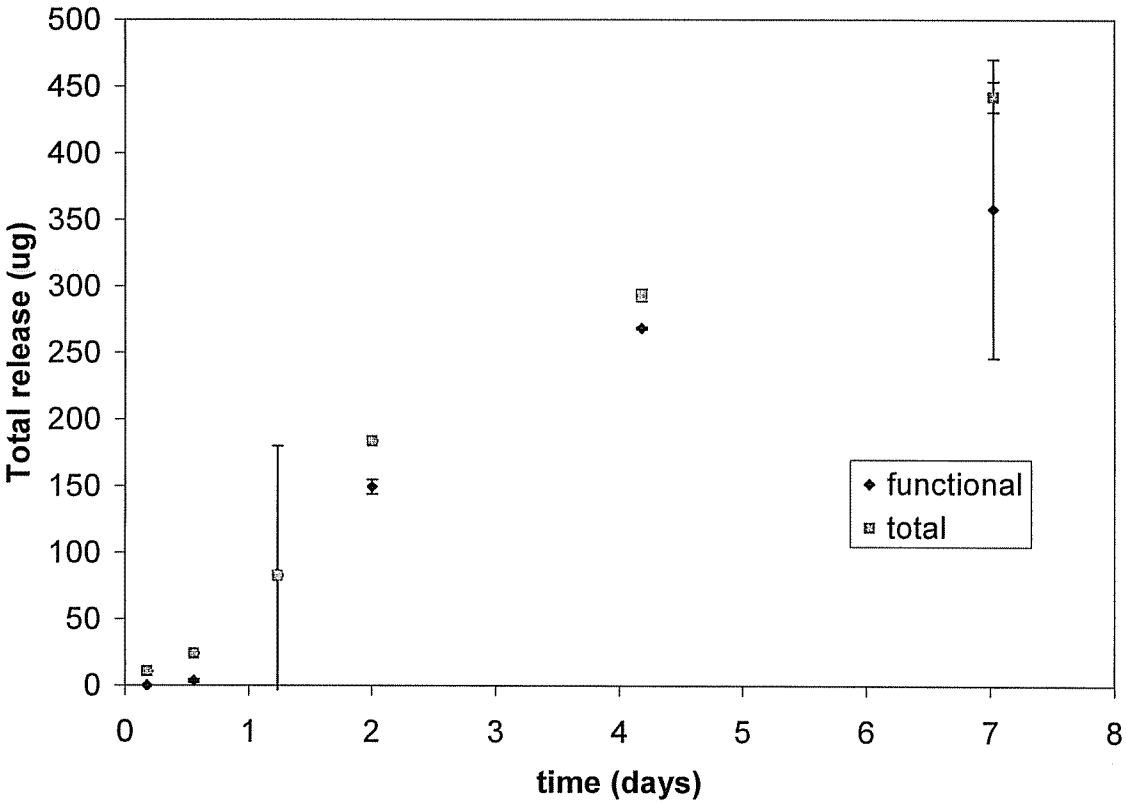

500
450
400
350
300
250
200
150
100
50
0
Total release (ug)
0
1
2
3
4
5
6
7
8
time (days)
functional
total

FIGURE 7

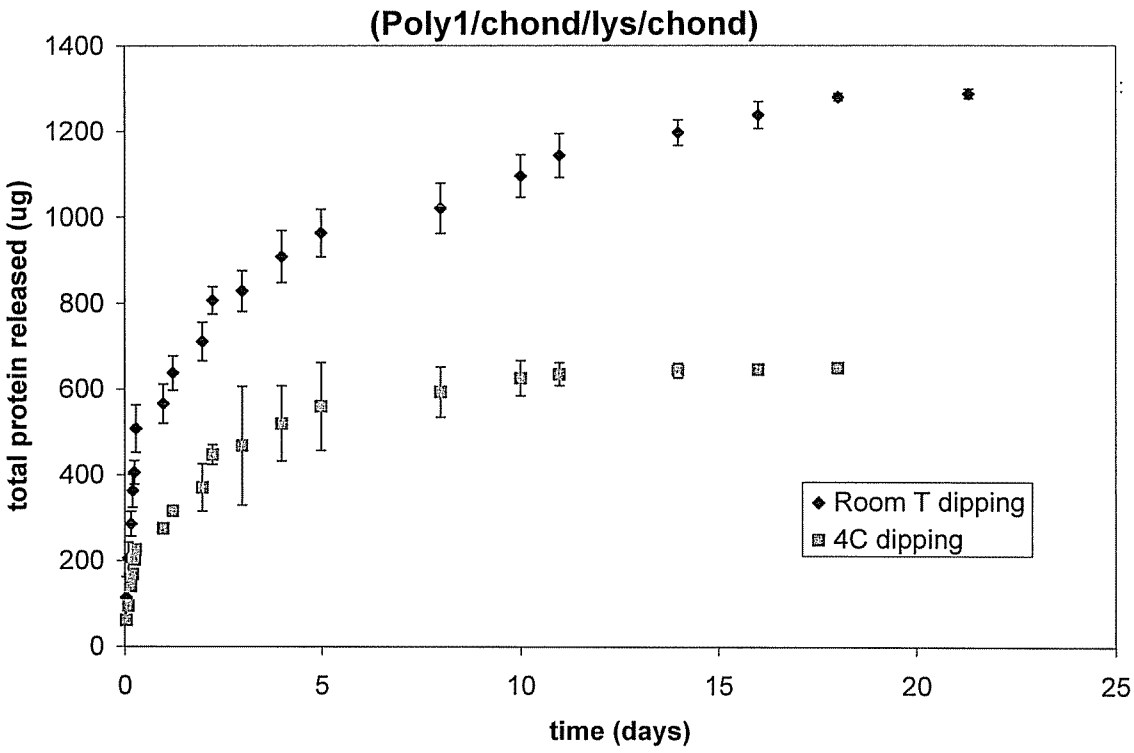

(Poly1/chond/lys/chond)
total protein released (ug)
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
time (days)
Room T dipping
4C dipping

FIGURE 8