

Immunospecific Gold Nanoparticles for Contrast Enhancement of Corneal Tissue Culture

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COLLEGE

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Abstract

There is a large and growing demand for corneas across the world. To increase the supply of corneas, the Orwin lab has been working to tissue-engineer corneas, and we have offered to use the Optical Coherence Microscope (OCM) to monitor the cells during tissue culture. However, the cells produce a low signal, so it is necessary to introduce cellularly specific extrinsic contrast. We have developed 90 nm gold spheres strongly bound to antibodies via polyethylene glycol chains that promise to "light up" corneal cells in tissue culture and indicate their phenotype. To date, we have optimized the creation of the spheres to ensure immunospecificity and stability. Furthermore, we have performed two cell labeling experiments with these spheres that, though they did not return the desired results, provided significant insight into the behavior of the cells.

Acknowledgments

This thesis would not have come about without the work of several people. More than anyone, I am indebted to my advisor, Prof. Richard Haskell, for his unceasing support and tireless dedication to this project. Another great help in this project was Alanna Weisberg '14. She has shown herself to be an extraordinarily competent scientist, and I am glad to leave this project in her hands. Many thanks are also due to Prof. Liz Orwin for growing cells and helping with the confocal imaging, and to her lab for allowing us to take up space. Finally, this thesis builds on the work of many people, over the course of 8 years. Thanks to: Chris Raub '04, Jamie Shoffeit '05, Megan Arman '06, Emily Hogan '07, David Coats '08, Clarence Chan '08, Albert Tsao '09, Rob Warren '10, Perry Ellis '11, and Oliver Hoidn '11.

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Chapter 1

Introduction

According to the National Eye Institute (NEI), approximately 40,000 cornea transplants are performed every year in the United States. Unfortunately, about 20 percent (8000 per year) of these transplants are rejected [5], necessitating a second transplant. An increase in the number of procedures is inconvenient for the patient at best; therefore, it is desirable to find ways to minimize the amount of rejection as well as increase the overall supply of tissue for cornea transplants.

1.1 Corneal Engineering

Prof. Liz Orwin's lab at Harvey Mudd College is attempting to overcome the challenges of cornea transplants by growing replacement corneas. This is done by electrospinning collagen fibers, then seeding cells from a patient who needs new corneas. However, the electrospun collagen does not possess the structural properties of corneal collagen, so the Orwin Lab is focused on finding ways to control the phenotype and regulatory mechanisms of the cells. It is hoped that through this process, the cells will reenact the initial formation of the corneas in fetal development, taking up the electrospun collagen and laying it back down in the native form, viz., a hexagonal close-packed array of 30 nm-diameter collagen fibrils.

In order to better understand the behavior of the cells in response to the treatments they receive, Prof. Orwin's lab would like to be able to monitor both the position and phenotype of the cells in the scaffold. Confocal microscopy, a standard biological imaging modality, has a high ($< 1 \mu\text{m}$ isotropic) resolution but can only image $25 \mu\text{m}$ deep. The high resolution makes confocal desirable, but human corneas are $500 \mu\text{m}$ thick, and

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the collagen scaffolds can be thicker, making confocal unusable for full 3D imaging. In contrast, the optical coherence microscope (OCM) trades high resolution for moderate resolution ($5\text{ }\mu\text{m}$ lateral, $10\text{ }\mu\text{m}$ axial) and over 1 mm of depth penetration at 850 nm wavelength. Consequently, the OCM was employed to monitor the cells.

Unfortunately, the collagen in the scaffold scatters too highly for the OCM to distinguish the cells, so Chris Raub '04 proposed a method, developed from a paper by Sokolov [11], wherein 35 nm gold nanoparticles would be applied to increase scattering of the cells via a process called indirect immunolabeling (see Figure 1.1)), the basic precepts of which are still used in this project [10]. Indirect immunolabeling has four key components: a target protein (we are targeting $\alpha 5\beta 1$ -integrin), a primary antibody (MAB1999) that is *anti-* the target protein, a secondary antibody (AP124F) that is *anti-* the primary antibody, and a label (both the gold nanoparticles and a fluorescent molecule on the AP124F). Indirect immunolabeling is implemented by first binding primary antibodies specifically to their target proteins on the surfaces of corneal cells. Then, secondary antibodies (anti-Ab1) are bound to nanoparticles via van der Waals forces. The antibody-gold is then allowed to bind to the Ab1-protein-cell *in vitro*. A schematic diagram of this process is shown in Figure 1.1.

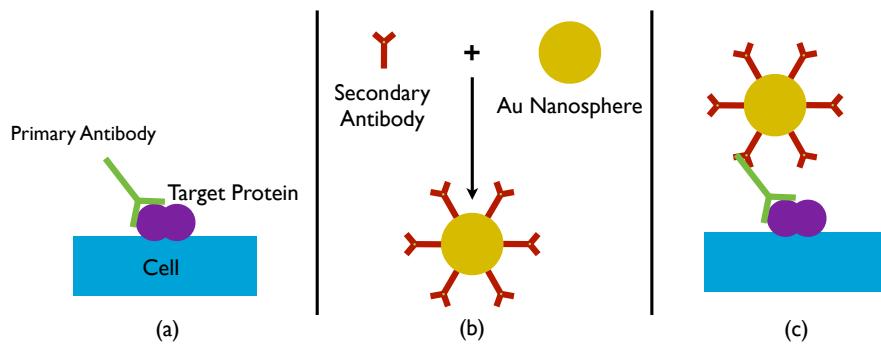


Figure 1.1 Stages of indirect immunolabeling presented schematically (not to scale). (a) The primary antibody, MAB1999, binds to the targeted surface protein, $\alpha 5\beta 1$ -integrin. (b) Secondary antibodies, AP124F, are bound to the surface of a gold nanoparticle. (c) A gold nanoparticle-secondary antibody complex binds to the primary antibody, which is in turn bound to the surface protein.

Jamie Shoffheit '05 [1], Megan Arman '06, and Emily Hogan '07 all followed on Raub's work to achieve labeling. The process they employed consisted of creating 35 nm diameter gold nanoparticles from a citrate re-

duction of Au(III) and binding the antibodies to the nanoparticles via van der Waals forces alone. Although Hogan was finally able to use this technique to produce a statistically significant increase in scattering in 2007, the scattering increase was not as great as was desired.

To address this, David Coats '08 did a number of studies to optimize the gold being used as the labeling agent. Coats performed extensive calculations using Mie theory to maximize scattering. Mie theory details the scattering pattern of particles on the order of or larger than the wavelength of light they scatter. As even a 35 nm nanoparticle cannot be approximated as a point when using 850 nm light, Mie theory provides a far more accurate prediction of the intensity of backscattered intensity than Rayleigh scattering theory. These calculations showed that for any diameter, a particle made of solid gold (versus a particle with an inner core of silica) gave the highest scattering to absorption cross-section ratio, as shown in Figure 1.2. As can also be seen in that image, C_{sca}/C_{abs} also increases with diameter, up to a point. However, the settling rate of the gold particles also had to be taken into account, as well as the availability of manufactured gold nanoparticles. With these multiple factors in consideration, it was decided that 90 nm diameter nanoparticles from Nanopartz would be used. With these improved gold particles, David Coats again performed imaging tests on a monolayer of cells. However, the same lack of obvious signal generation prompted even further investigation.

One concern regarding the labeling system was that the antibodies were bound to the gold with only van der Waals forces. Rob Warren '10 [13] discovered a procedure in a paper by Lowery et al. [7] by which increased binding had been achieved for immunolabeling. The procedure is called PEGylation because of its use of polyethylene glycol polymer chains; a schematic diagram of the process is shown in Figure 1.3. The procedure consists of using a polyethylene glycol (PEG) polymer chain functionalized at one end with orthopyridyl disulfide (OPSS) and at the other with an N-Hydroxysuccinimide ester (NHS). The OPSS-PEG-NHS is incubated with the antibody for 24 hours, in which time the NHS ester reacts with a lysine in the antibody, leaving the NHS ester free in solution and the antibody attached to the OPSS-PEG. This OPAb, as we call it, is then incubated with the gold for 24 hours, so that the OPSS group splits at the disulfide bond and the PEG chain attaches to the gold via a thiol bond, which has a strength slightly less than that of a covalent bond and much larger than that of a van der Waals bond. This should ensure that the antibody is firmly attached to the gold. The second part of the procedure is to prevent any other molecules from binding with the gold. This is accomplished by

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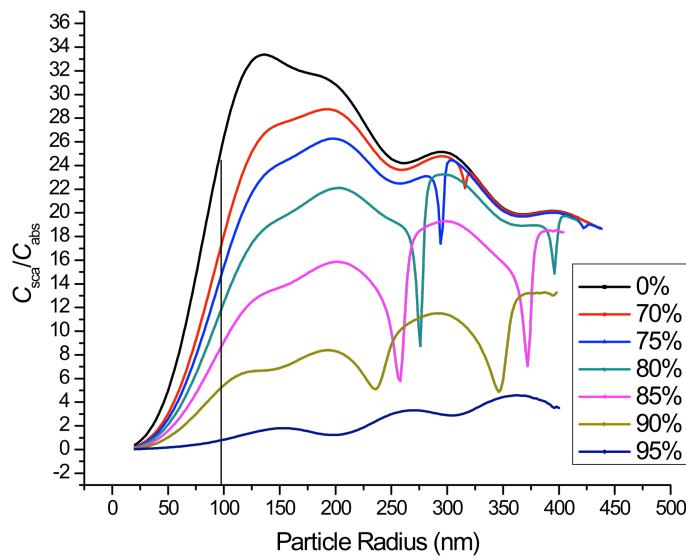


Figure 1.2 Plot of the ratio of the scattering cross section C_{sca} to the absorption cross section C_{abs} as a function of total particle diameter, calculated via Mie theory. Line color, as indicated by legend, corresponds to percent of total diameter taken up by silica inner core. Index of refraction values used are $n_{Au} = 0.194 - 5.527i$, $n_{silica} = 1.44$, and $n_{water} = 1.33$ for the surrounding region. From reference [2].

binding another PEG chain to the gold, of which one end is functionalized with a thiol group (SH) that then forms a thiol bond with the gold. This should fill any space left after the addition of the OPAb.

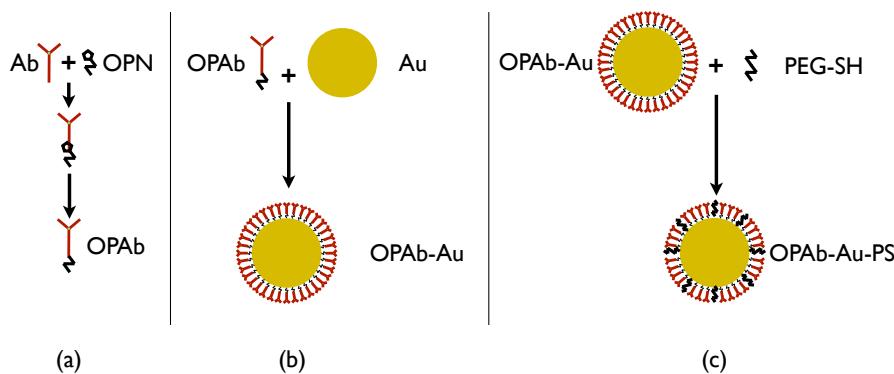


Figure 1.3 Schematic diagram of the PEGylation process. (a) The OPSS-PEG-NHS (OPN) binds to the antibody (Ab) to form OPAb. (b) The OPAb binds to the Au nanosphere to form OPAb-Au. (c) The PEG-SH fills in the gaps on the surface of the OPAb-Au, forming OPAb-Au-PS and protecting the sphere.

Unfortunately, these tests also failed to produce the desired specific increase in scattering, so in the summer of 2010 Oliver Hoidn and Perry Ellis '11 undertook a reexamination of the PEGylation protocol. Several significant results emerged from their studies that indicated problems with the PEGylation protocol. First, the Nanopartz gold nanoparticle solution, though its pH is advertised as between 6 and 8, was actually measured at a pH between 5 and 5.5 [3] due to the lack of a buffer in the solution. However, if commercial PBS is added, the salt in that solution screens the negative capping agent on the gold nanoparticles, thus eliminating the mutual repulsion between the nanoparticles and causing them to agglomerate and fall out of solution. To remedy this, a buffer solution made of $\text{Na}_2\text{HPO}_4 \cdot 7\text{H}_2\text{O}$ and $\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$ was added to the gold to achieve a total salt concentration of 10 mM. This concentration was chosen as it provides a sufficient level of buffering without screening the capping agent too much. However, over the course of the several days required for the full PEGylation process, it was found that the final immunolabeled gold nanoparticles still suffered from a high rate of agglomeration. A footnote was then found in Lowery et al. [7] that noted that PEG-SH cannot perform its protective function unless it has a molecular weight of at least 5 kDa. As the PEG-SH used up to that point had been of molecular weight 1.2 kDa, it

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had not protected the gold.

Thus, after Oliver and Perry concluded their work in the summer of 2010, it remained to readjust the PEGylation protocol for 5 kDa PEG-SH, and to use that updated protocol to once again try to significantly increased specific immunolabeling. In addition, it was discovered that the NHS ester used to bind the OPN to the antibody can undergo hydrolysis, rendering it incapable of binding; therefore, it was also necessary to examine the hydrolysis of the NHS ester. To date, the issue of NHS hydrolysis has been settled (Chapter 2) and the PEGylation protocol has been optimized with the 5 kDa PEG-SH (Chapter 3). The optimized protocol produces structural results consistent with the model of PEGylation we have developed (Chapter 4). In addition, the 5 kDa PEG-SH appears to provide excellent long-term protection against agglomeration of the spheres. Spheres made with the optimized protocol have been used in two labeling experiments (Chapter 5 and Chapter 6), which have provided further insights into the immunolabeling process.

Chapter 2

Addition of Antibodies to Nanospheres

At the end of the summer of 2010, Oliver Hoidn and Perry Ellis had determined that the optimal number of OPSS-PEG-antibody (OPAb) molecules per nanosphere was approximately 2000; however, there were significant concerns as to whether the OPSS-PEG-NHS (OPN) was successfully binding to the lysines on the antibody, or whether monolayer formation was simply the result of the antibodies binding to the nanospheres via van der Waals forces. The OPN reaction occurs by substituting the NHS ester for a primary amine, such as the one found on the functional groups of lysines in an antibody. A diagram of this reaction is shown in Figure 2.1.

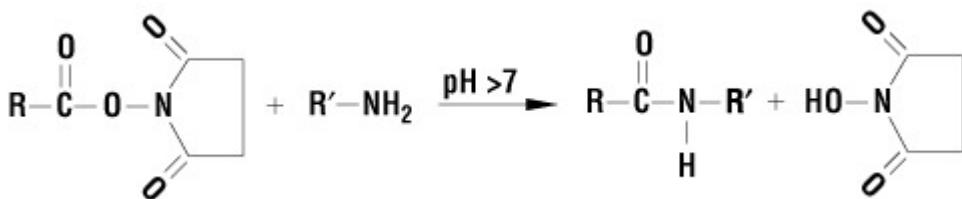


Figure 2.1 Schematic diagram of the OPN+antibody→OPAb reaction. **R** represents the OPSS-PEG, and **R'** represents the antibody. The reaction is favored in basic conditions. From reference [9]

OPN comes in a lyophilized form, and the reaction with the antibody does not occur until the OPN is in solution. However, once the OPB is in solution, a competing reaction begins in which hydrolysis occurs and the NHS ester is replaced with a hydroxyl group instead of an amine. This

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renders the molecule unable to bind to antibodies, and the half-life of the hydrolysis reaction can be on the order of minutes at pH 8 [6]. Consequently, there was a concern that a large portion of the OPN used in the OPN+antibody→OPAb reaction was not binding to the antibody.

Fortunately, a direct physical measurement can be used to quantify the hydrolysis of the NHS ester. The free NHS ester in solution absorbs at 260 nm much more strongly than the bound ester [8]. Therefore, the Cary 5000 UV-Vis-IR Spectrophotometer was used to monitor the absorption at 260 nm over the course of several hours. The results of this measurement are shown in Figure 2.2.

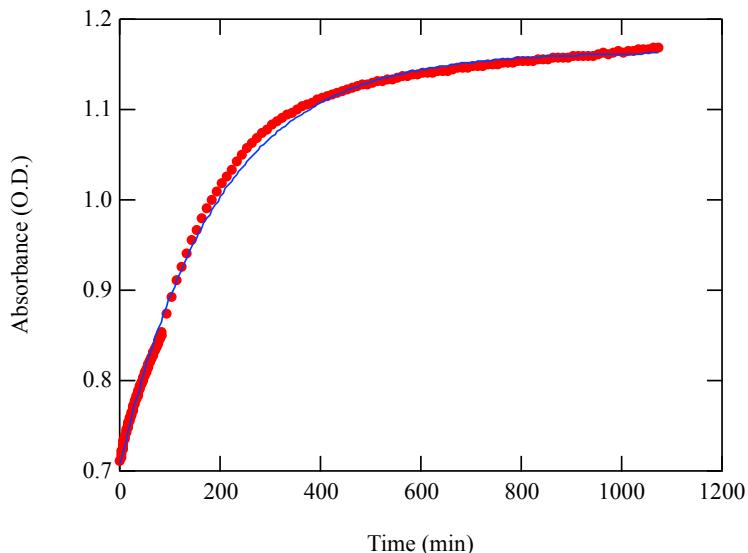


Figure 2.2 Plot of the absorbance of the OPN solution over time. The reaction rate seems to be proportional to concentration, giving a simple first-order rate law. The lower density of points at ~ 80 minutes occurred because the spectrophotometer was set to record a spectrum every 10 minutes rather than every 1 minute. The blue line displays a fit to $A = C_1 + C_2 e^{-C_3 t}$. The fitted values were $C_1 = 1.16$, $C_2 = -0.458$, and $C_3 = 0.0052$

Based on the coefficient of the exponent, $C_3 = 0.00523 \text{ min}^{-1}$, we can calculate that the half-life of NHS ester hydrolysis at pH 7.5 is

$$\tau_{1/2} = \frac{\ln 2}{C_3} = 133 \text{ min}$$

or about two hours.

Two conclusions can be drawn from this: first, there is very little danger of having no bound NHS remaining when the protein is added, since that should occur at the most 10 minutes after the OPN solution is created (and will most likely be less than five minutes after solution creation). Second, this confirms the need to incubate the protein with the OPN overnight. Since both hydrolysis of the NHS and the reaction with the lysine work on a similar mechanism, their rates can be expected to be comparable. Thus, in order to create as much OPAb as possible, at least four hydrolysis half-lives are necessary to achieve > 90% yield. However, since the hydrolysis is nontrivial on that time scale, OPN should be used in a factor of 2 excess in order to facilitate maximal protein binding. Therefore, in the PEGylation procedure, we will use 2,000 antibodies per Au nanosphere and 4,000 OPN molecules per nanosphere (see Appendix A).

Chapter 3

Addition of PEG-SH to Nanospheres

With the questions about OPN-to-antibody and OPAb-to-nanosphere binding settled, it still remained to determine the optimal concentration of PEG-SH (PS). The PEG-SH is used expressly for the purpose of protecting the gold nanospheres from agglomerating when placed in a salt solution, e.g. the phosphate-buffered saline (PBS) solution present in a cell culture. However, Ellis and Hoidn found that the 1 kDa PEG-SH used since PEGylation was first introduced [13] failed to adequately protect the spheres, leading to a significant degree of agglomeration, as shown in Figure 3.1. A footnote found by Ellis and Hoidn in Lowery et al. [7] noted that PEG-SH with a molecular weight less than 5 kDa does not protect gold, explaining the failure of the 1.2 kDa PEG-SH.

At the end of the summer of 2010, 5 kDa PEG-SH had not yet been used or characterized, so a completely new optimization process had to be applied. This consisted of measuring the radii of the gold spheres immediately after the addition of a variety of concentrations of 5 kDa PEG-SH (section 3.1); measuring the radii of the same solutions after an incubation period (section 3.2); and measuring the radii of some solutions after addition of salt solution (section 3.3). These measurements yielded a monolayer number for 5 kDa PEG-SH of approximately 50,000 PS/Au. Strong protection of the nanospheres was also demonstrated at 10,000 PS/Au. Therefore, 10,000 PS/Au was used as the concentration for the full protocol, as it provides protection, and there should already be a monolayer of OPAb on the surface of the nanospheres.

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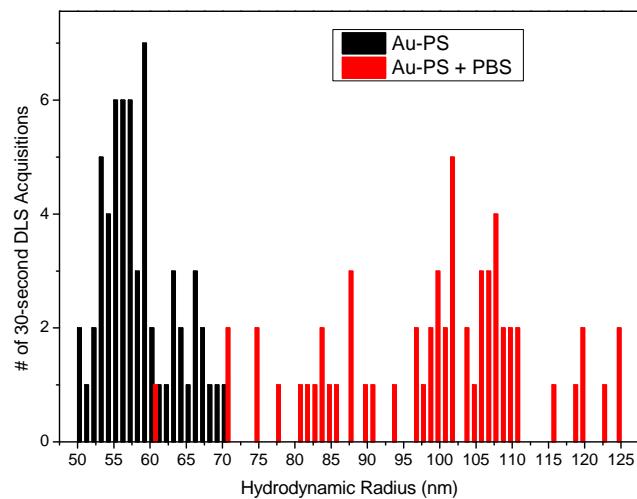


Figure 3.1 Histogram of radii of 30-second DLS acquisitions of 10^7 1 kDa PS/Au with and without PBS from the summer of 2010. The distribution is noticeably shifted to the right and flattened after the addition of PBS. Data taken by Ellis and Hoidn [3].

3.1 Titration Study

A titration curve was made by adding 5 kDa PS to 90 nm gold nanospheres ($R=52$ nm) in varying concentrations, from 1000 PS per nanosphere to 10^7 PS per nanosphere; the broad range was used to determine the range of concentrations in which the monolayer formed. The hydrodynamic radii of these PEGylated nanospheres were then measured using the Dynamic Light Scattering (DLS) instrument, taking 15 30-second acquisitions of each solution and discarding the first three to account for temperature acclimation. The results of these exploratory measurements are shown in Figure 3.2.

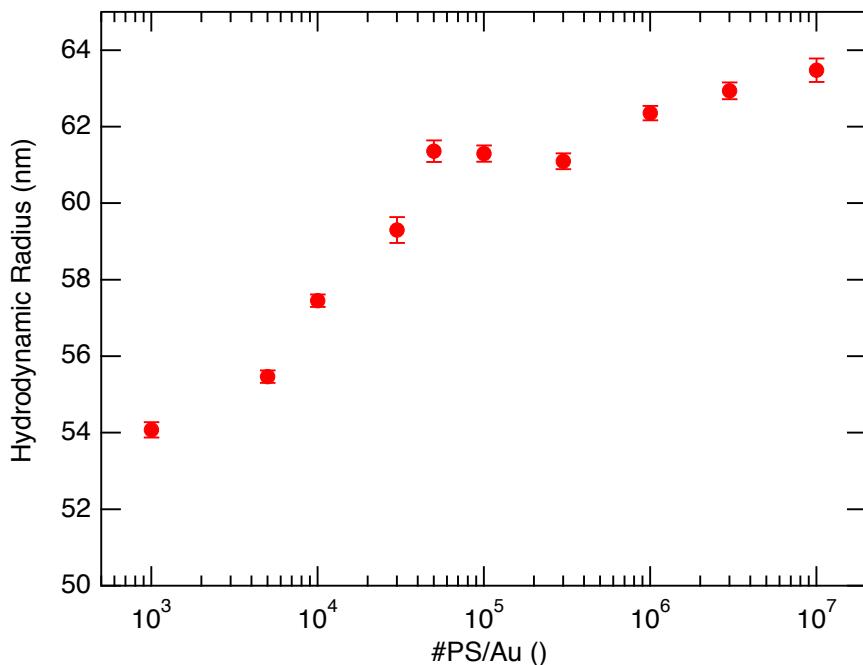


Figure 3.2 Plot of hydrodynamic radii of Au nanospheres from 1,000 to 10^7 PS/Au less than 30 minutes after addition of PS.

This plot shows the behavior of a rapid rise followed by a plateau that is expected of a species forming a monolayer on a surface. The plateau begins to appear around 100,000 #PS/Au, so two more measurements were taken with a spread of concentrations around that range. A plot of the averages of the radii of the repeated concentrations are shown in Figure 3.3. This

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data suggests that the monolayer is formed at approximately 50,000 #PS/Au, with a radius of 60.4 ± 0.3 nm.

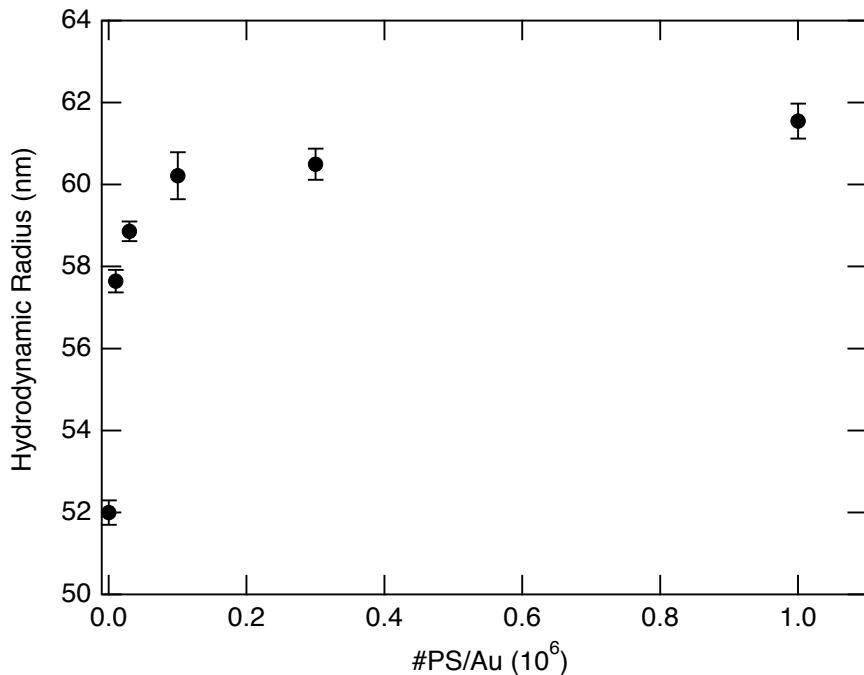


Figure 3.3 Plot of hydrodynamic radii of Au nanospheres at 10,000, 30,000, 100,000, 300,000, and 10^6 PS/Au less than 30 minutes after addition of PS. Points are formed by taking the mean and standard error of three independent measurements at each concentration.

3.2 Time Study

The same samples used in the titration study were measured again after 48–72 hours of incubation, producing the radii shown in Figure 3.4.

The plateau in this graph is slightly sharper than in Figure 3.3, indicating that van der Waals forces and thiol bonding processes are in competition, with van der Waals binding dominating immediately after addition, but the lower-energy thiol bonds dominating after incubation time. This leads to the increased radius of the lower-radius samples and the decreased radius of the higher-radius samples. However, the plateau region still has $R = 60.3 \pm 0.3$ nm, as a second indication of a monolayer. Clearly, it is

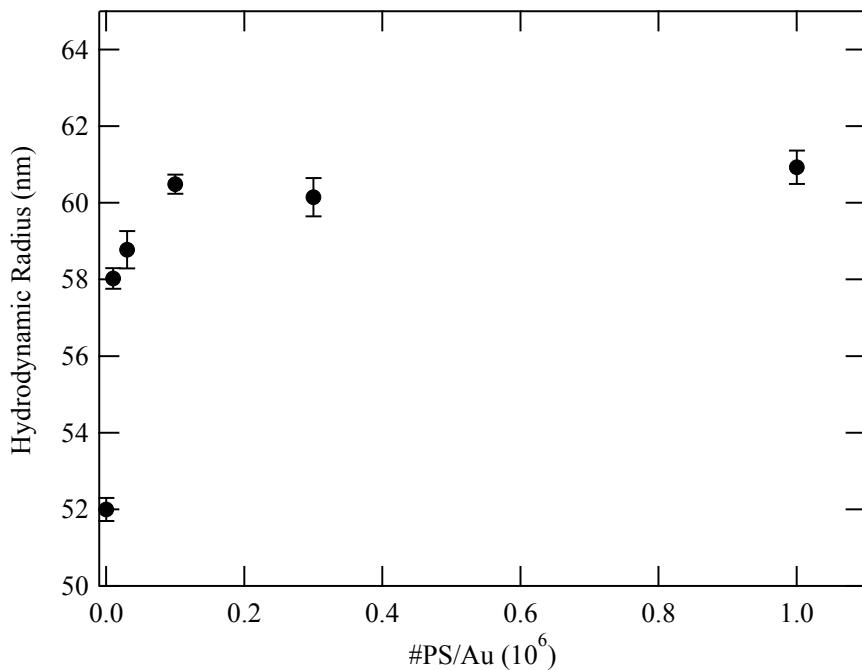


Figure 3.4 Plot of hydrodynamic radius of Au nanospheres at the same concentrations as in Figure 3.3 48–72 hours after addition of PS. Points are formed by taking the mean and standard error of three independent measurements at each concentration.

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essential that PEG-SH be allowed to incubate with spheres to allow for the PEG-SH binding to reach equilibrium.

More information about the final monolayer state can be gained from determining the apparent number of PEG-SH molecules bound to the nanosphere. A single 5 kDa PEG-SH molecule, with a density of $1.11 \frac{\text{g}}{\text{cm}^3}$, has a volume of

$$V_{\text{5 kDa PEG-SH}} = \frac{5 \text{kDa}}{1.11 \frac{\text{g}}{\text{cm}^3}} = 7.5 \text{ nm}^3$$

This means that a 5 kDa PEG-SH monolayer has, based on the change in hydrodynamic radius,

$$\#_{\text{5 kDa PEG-SH}} = \frac{\frac{4}{3}\pi((60.5 \text{ nm})^3 - (51.0 \text{ nm})^3)}{V_{\text{5 kDa PEG-SH}}} = 48,400 \pm 900 \text{ 5 kDa PEG-SH}$$

This indicates that the measurement of the plateau as beginning at 50,000 PEG-SH per nanosphere is correct. This also allows us to get a sense of the effective footprint of a PEG-SH molecule as it sits on the gold. At monolayer concentration, the area on the surface of the gold taken up by each PEG-SH molecules is

$$A_{\text{PS}} = \frac{4\pi(51.5 \text{ nm})^2 / \text{Au}}{47,500 \frac{\text{PS}}{\text{Au}}} = 0.70 \pm 0.03 \frac{\text{nm}^2}{\text{PS}} = 70 \pm 3 \frac{\text{\AA}^2}{\text{PS}}$$

This size is determined partially by the atomic size of the sulfur atom ($D = 2 \text{\AA}$), but mostly by the extent to which the PEG chain is bunched; clearly, most of the effective width comes from the bunching.

3.3 Protection Study

As mentioned above, the main reason for using 5 kDa PEG-SH is to prevent the Au nanospheres from agglomerating. The Au nanosphere solution includes a negatively charged capping agent that makes the spheres repel each other; when the solution is buffered at pH ~ 7.5 to prevent antibodies from denaturing during the full immunogold procedure, positive ions are introduced into the solution that neutralize the capping agents, causing the gold nanospheres to agglomerate. Theoretically, PEG-SH would prevent this from happening, but 1 kDa PEG-SH does not, as shown in Figure 3.1.

Therefore, the protection capabilities of 5 kDa PS were tested by adding PEG-SH to the Au nanospheres in various concentrations, then mixing those solutions in equal volumes with commercial PBS, which has a salt

concentration of approximate 150 mM. The spheres were allowed to incubate for at least 30 minutes with the PBS, then measured in the DLS. Selected results from those measurements are shown in Figure 3.5.

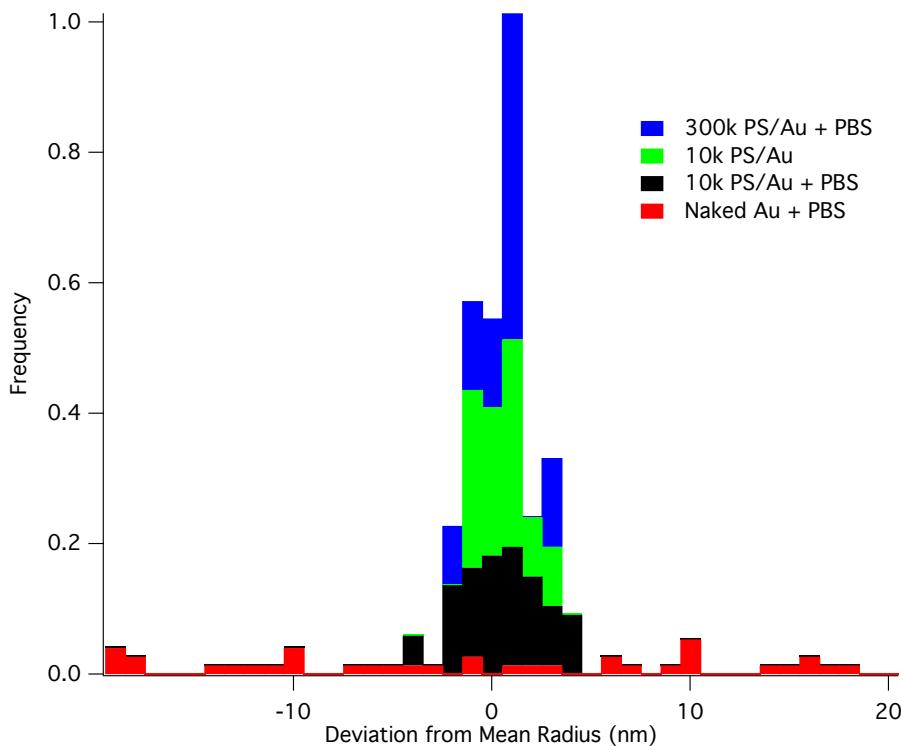


Figure 3.5 Stacked histograms of differing concentrations of Au-PS with and without PBS. The naked gold is significantly broader than any of the other distributions.

For all but the naked gold, almost all acquisitions are within 3 nm of the mean; this is also true of the 300k PS/Au without PBS from the summer of 2010. However, with just 10k 5 kDa PS/Au, the width of the distribution barely widens when PBS is added—a stark contrast to the addition of PBS to 300k 1 kDa PS/Au. Furthermore, there was a ~15 nm increase in average radius between the 1 kDa PS spheres with and without PBS. In the case of the 10k 5 kDa PS/Au, the difference in average radius was negligible: 0.09 nm.

From observing the lack of change in both average radius and the change in radial distribution when using the 5 kDa PEG-SH, it is clear that the 5

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kDa PEG-SH fully protects the Au nanospheres against capping agent neutralization. There is, however, a noticeable difference between the 10k and 300k PS/Au samples; the 300k is slightly narrower, indicating that it offers slightly more protection, consistent with the 300k PS/Au solution being on the plateau while the 10k PS/Au is still on the rising part of the titration curve.

Chapter 4

Results of the Full Protocol

Several fully labeled and protected nanosphere samples were created during the '11-'12 year. The protocol used was adapted from Oliver Hoidn and Perry Ellis's report [3], using 2,000 antibodies per Au nanosphere and the curve-elbow value 10,000 PEG-SH molecules per Au nanosphere. Detailed documentation of the PE Gylation protocol can be found in Appendix A.

The progress of the protocol was monitored by a DLS radius measurement at five or six stages:

1. Immediately after the addition of the OPAb to the Au nanoparticles
2. 24 hours after the addition of the OPAb to the Au nanoparticles
3. Immediately after the addition of the PEG-SH to the OPAb-Au nanoparticles
4. 24 hours after the addition of the PEG-SH to the OPAb-Au nanoparticles
5. After dilution of the OPAb-Au-PS nanoparticles with an equal volume of PBS, to check for protection
6. (For most but not all samples) 48 hours after the addition of PEG-SH to the OPAb-Au nanoparticles

The results of these measurements are shown in Figure 4.1. The data shows an immediate increase of 6.1 ± 0.6 nm upon the addition of the OPAb, followed by slight (<0.1 nm) gains after 24 hours of incubation. AP124F is an IgG antibody and has dimensions of approximately 14.5 nm \times 8.5 nm \times 4.0 nm [12] as shown in Figure 4.2; since the NHS replacement can

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occur on any lysine or N terminus (of which there are several), a 6.1 nm increase in radius is reasonable when all spatial orientations are taken into account.

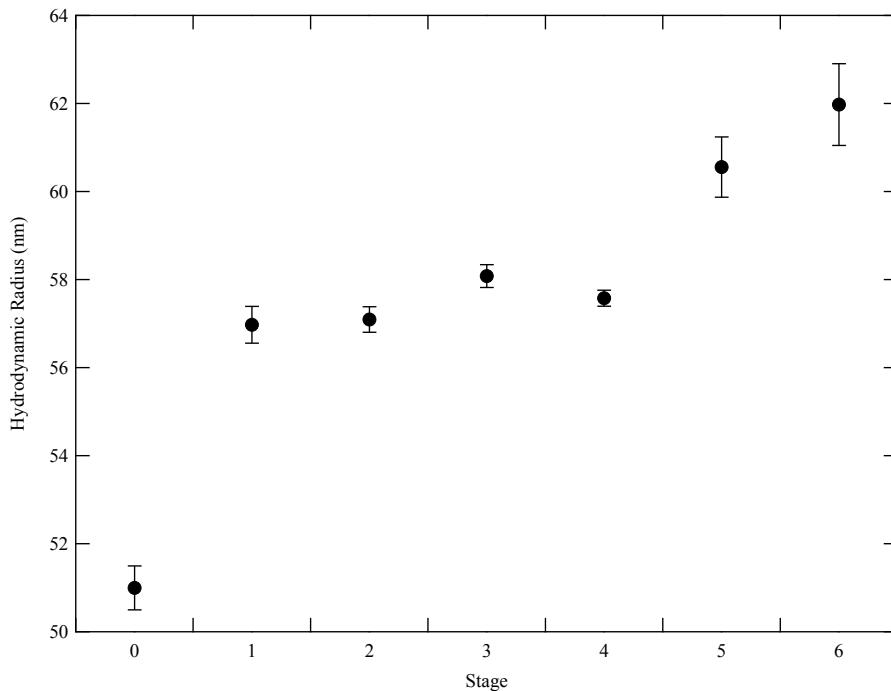


Figure 4.1 Plot of hydrodynamic radii of multiple solutions at each step in the protocol. Step numbers correspond to: 0 – Naked Au, 1 – Immediately after the addition of the OPAb, 2 – 24 hours after the addition of the OPAb, 3 – Immediately after the addition of the PEG-SH, 4 – 24 hours after the addition of the PEG-SH, 5 – 48 hours after the addition of PEG-SH, 6 – After dilution with equal parts PBS.

Additional analysis can be performed by using the same number estimation as in Chapter 3. An OPAb conjugate should have a volume of

$$V = V_{\text{PEG}} + V_{\text{Ab}} = \frac{2.1 \text{kDa}}{1.11 \frac{\text{g}}{\text{cm}^3}} + \frac{160 \text{kDa}}{1.35 \frac{\text{g}}{\text{cm}^3}} = 200 \text{ nm}^3$$

Examining the hydrodynamic volume change after the addition of PEG-SH, this corresponds to

$$\frac{4}{3}\pi[(57.1 \text{ nm})^3 - (51 \text{ nm})^3] / \frac{200 \text{ nm}^3}{\text{OPAb}} = 1120 \pm 30 \text{ OPAb}$$

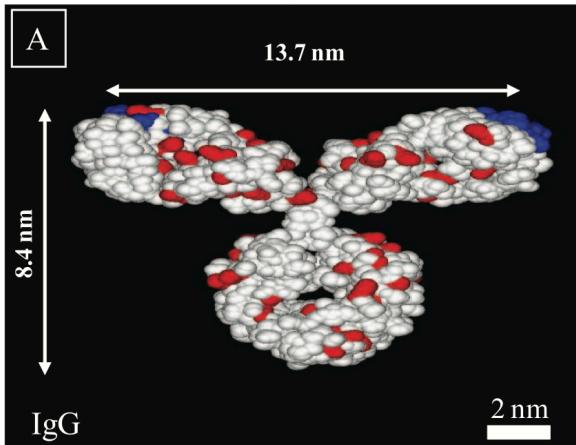


Figure 4.2 Structural dimensions of an IgG antibody. From reference [12].

However, this may be an over-estimate, as the $1.35 \frac{\text{g}}{\text{cm}^3}$ density is for the crystalline state of protein [4]; the actual effective volume of the OPAb in solution may be larger. Further uncertainty is introduced by the complexity of the diffusion of an Au nanosphere with over 1000 OPAb molecules attached to it. Therefore, this calculation serves primarily as an order-of-magnitude check; in that sense, 1120 OPAb/Au compares quite favorably to the 2000 OPAb/Au in solution.

We can again perform a calculation of effective footprint:

$$A_{\text{OPAb}} = \frac{4\pi(51 \text{ nm})^2 / \text{Au}}{1120 \frac{\text{OPAb}}{\text{Au}}} = 29.2 \pm 1.6 \frac{\text{nm}^2}{\text{OPAb}}$$

This is considerably larger than the effective width of the PEG-SH, indicating that the OPAb molecules on the nanosphere sterically hinder other OPAb molecules from forming thiol bonds with the nanosphere surface. Since the binding mechanism between the PEG chain and the gold surface is the same, this means that there is likely additional room for thiol bonds on the surface, which means that the PEG-SH should fill in gaps on the surface of the sphere.

Performing the same volumetric analysis on the change in radius from OPAb-Au to OPAb-Au-PS, we see that the number of PS molecules bound to the OPAb-Au is approximately

$$\frac{4}{3}\pi[(57.6 \text{ nm})^3 - (57.1 \text{ nm})^3] / \frac{7.5 \text{ nm}^3}{\text{PS}} = 2780 \pm 650 \text{ PS.}$$

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This number is the right order of magnitude, given that 10,000 PS/Au were added, and only the gaps on the surface are expected to be filled.

The addition of PEG-SH brings the total number of thiol bonded PEG chains on the Au nanosphere surface to approximately 4,000. Though that is not quite the number of PEG-SH molecules that demonstrated protection in Ch. Chapter 3, the combination of the 4,000 PEG chains and the antibodies clearly protected the spheres from agglomeration. This is evidenced by the lack of radius increase when the fully labeled and protected nanospheres are diluted with an equal volume of commercial PBS solution, as shown in Figure 4.1. Since the radial growth of the spheres matched its predicted behavior fairly well, the decision was made to progress to using the nanospheres to label a cell culture monolayer.

Chapter 5

Results of the 6 March Labeling Session

With the PEGylation process fully optimized, we took the first step towards immunolabeling a full 3D artificial cornea, namely immunolabeling of a monolayer of cells on a microscope coverslip. The cells used were human dermal fibroblasts (HDFs) that express $\alpha 5\beta 1$ -integrin, the same surface protein that we are targeting on the corneal cells. Performing immunolabeling on the monolayer allows assessment of the efficacy of the indirect immunolabeling process only, disregarding the collagen and removing the financial and temporal costs of building a complete corneal construct.

5.1 Structure of the Immunolabeling Experiment

Several different preparations of cells were used to determine the efficacy of the immunolabeling process. Each of them adds one or more key components of the process, which should yield very little increase in the scattering contrast until the full labeling system is assembled. The 6 preparations and their expected outcomes are described in Table 5.1.

The cells were prepared according to the procedure found in Appendix B; in brief, the procedure is

1. Fix cells with paraformaldehyde
2. Permeabilize with Triton-X
3. Label the nuclei with Sytox Green and the actin filaments with phalloidin (fluorescent stains); simultaneously perform immunoblocking

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with goat serum.

4. Add primary antibody if appropriate for a given preparation
5. Add secondary labeler (if any)

In between each stage, the sample is washed to remove residues of the previously applied label. Each preparation had three different samples (except for the 2Au preparation, which unfortunately had only two) to minimize intrinsic variation during inter-preparation comparison. After labeling, each sample was imaged in three different places with the confocal microscope, using both fluorescence and backscattering modes, and then each sample was imaged at five different $500\text{ }\mu\text{m} \times 500\text{ }\mu\text{m}$ field of view locations with the OCM (except for 2Au, for which each sample was sampled at 10 different locations).

Table 5.1 Description of the six preparations used in the 6 March immunolabeling experiment; each preparation is described by whether the primary antibody (MAB1999) was added, what secondary labeler (AP124F, AP124F PEGylated to Au nanospheres, or naked Au nanospheres) was added, and whether or not an increase was expected in backscattering or fluorescence.

Preparation Name	Primary Antibody?	Secondary Labeler?	+Scattering Expected?	+Fluorescence Expected?
Cells Only	No	No	No	No
2 only	No	Secondary Ab	No	No
1–2	Yes	Secondary Ab	No	Yes
2Au	No	OPAb-Au-PS	No	No
1–2Au	Yes	OPAb-Au-PS	Yes	Yes
Au	No	Naked Au	Yes but non-specific	No

The first preparation is just cells, grown on a coverslip. In the confocal microscope, a Zeiss LSM 510, we expect to see green fluorescence in the shape of the nuclei from the Sytox Green and red fluorescence in the shape of the actin filaments within the cell from the phalloidin. In the OCM, we expect to see backscatter contrast between the cells and the coverslip; however, the amount of backscattering from the cells should be quite low.

The next preparation is cells with the addition of only the secondary antibody, AP124F. The F in the AP124F signifies the presence of a fluorescent marker, specifically a fluorescein isothiocyanate (FITC) molecule which has an emission spectrum peak at 521 nm. Since the AP124F binds specifically to the MAB1999, and no MAB1999 is present on the surface of the cells, all of the AP124F should be washed off. As a result, the 2 only preparation should be identical to the cells only preparation.

The 1-2 preparation, in contrast, has MAB1999 present. The MAB1999 should bind to the integrins on the surface of the cell, and the AP124F should bind to the MAB1999 in turn. This should manifest itself in the confocal microscope as fluorescence signal at 521 nm. The fluorescence should be localized to the integrins, which are situated in streaks at the edges of the cell. As the AP124F and MAB1999 do not increase the backscattering, the OCM images of the 1-2 preparation should be equivalent to the images of unlabeled cells.

The 2Au preparation should behave just like the 2 only preparation: the lack of MAB1999 should mean that the OPAb-Au-PS spheres cannot bind to anything, and should be washed off. This should result in confocal and OCM images equivalent to those of unlabeled cells.

The 1-2Au preparation should show fluorescence in the pattern of integrins for the same reason as the 1-2 preparation. In addition, the 1-2Au preparation should have gold nanoparticles localized to the integrins, increasing the backscattering signal observed in the OCM.

The naked Au nanospheres have no fluorescent marker, so an increase in fluorescence cannot occur. A scattering increase is expected from the application of the naked Au; however, as the naked spheres have no specific binding mechanism, their binding will not be localized. Instead, the naked Au spheres will likely bind to the coverslip and cells in a homogenous manner through van der Waals forces.

Together, these preparations serve as a set of controls. In the event that the 1-2Au system fails to show any scattering contrast increase, the 2 only and 1-2 only can be used to demonstrate that the AP124F does specifically bind to the MAB1999. This converse is also true: if the 2 only (or 2Au only) show increases in fluorescence or scattering, non-specific binding is occurring, indicating that some part of the PEGylation or labeling process is faulty.

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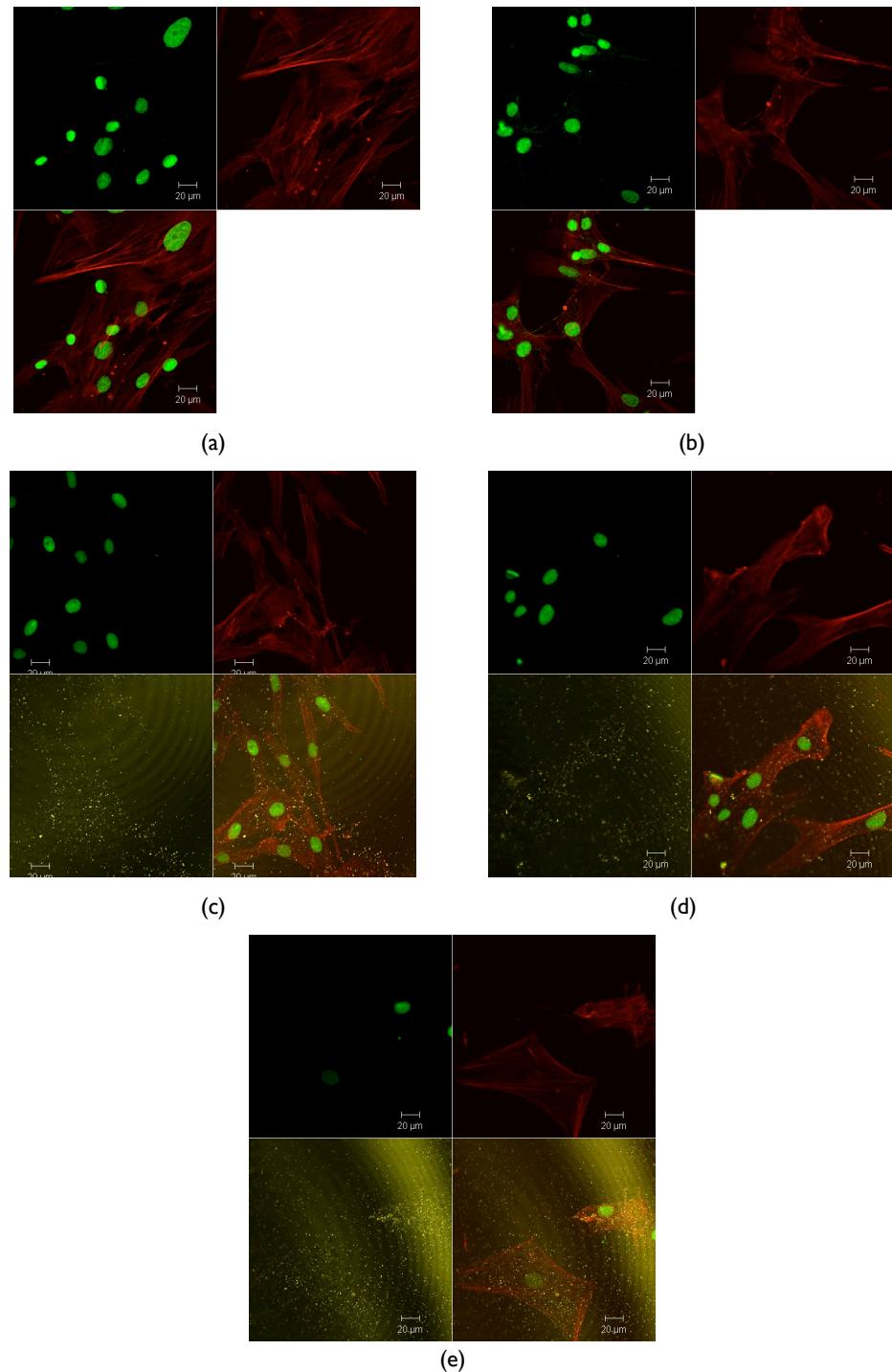


Figure 5.1 Confocal images of labeled preparations. Each image is a split view, showing Sytox and AP124F fluorescence (top left), phalloidin fluorescence (top right), backscattered light (c–e only; bottom left), and the composite view (bottom right, a and b; bottom right, c–e). Images correspond to preparations: (a) 2 only; (b) 1–2; (c) 1–2Au; (d) 2Au; (e) Au.

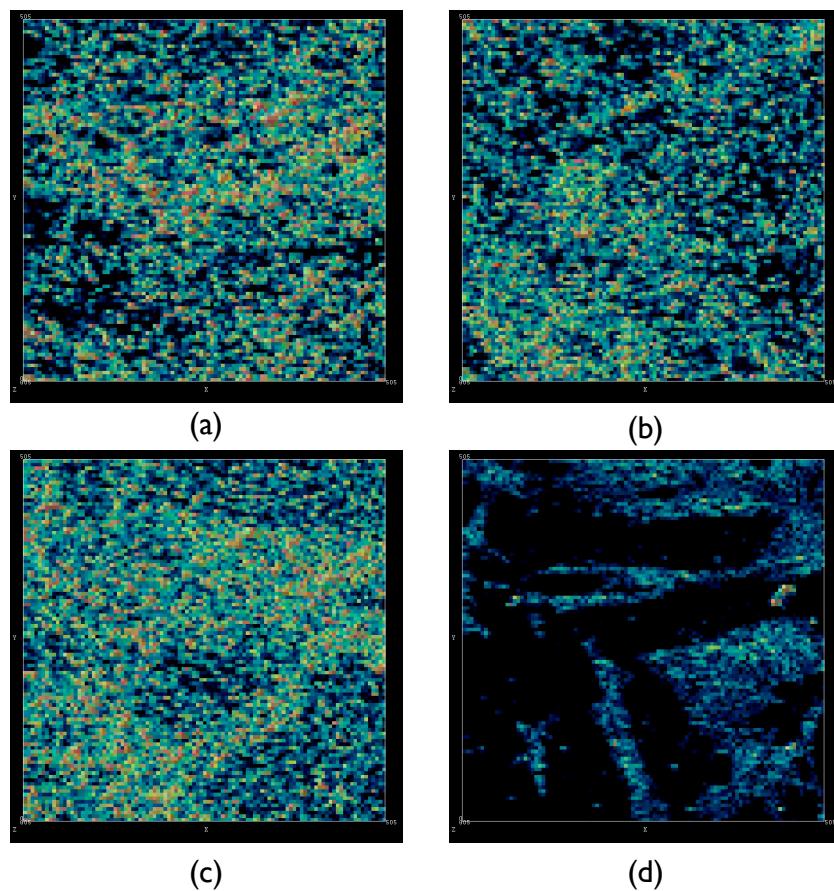


Figure 5.2 OCM images of labeled preparations. Images correspond to preparations: (a) 1–2Au; (b) 2Au; (c) Au; (d) Cells only.

5.2 Results of the Immunolabeling Experiment

Representative confocal images for each labeled sample are shown in Figure 5.1. Examining the between the 2 only and 1–2 confocal images reveals trails of green dots away from the nucleus only in the 1–2 sample; this is the expected pattern of labeled integrins. The appearance of stained integrins in only the 1–2 preparation indicates that both the primary and secondary antibodies bind only to the integrin and primary antibody, respectively. The samples with gold, however, are not as encouraging. Appearance of distinguishable cellular features in the back-reflectance channel indicates that the gold spheres bind to the cells—and to the coverslip—regardless of the presence of either the primary or secondary antibody. Nevertheless, cellular features are more easily distinguished in the 2Au samples, and most easily in the 1–2Au sample. This seems to indicate that some specific binding is occurring, but that a large amount of nonspecific binding is occurring as well.

Representative OCM images for the preparations labeled with gold as well as unlabeled cells are shown in Figure 5.2. Clearly, all three gold-labeled preparations show a significant increase in scattering compared to the unlabeled cells. However, as in the confocal images, the Au and 2Au preparations show a strong increase in scattering, and allow for cellular features to be distinguished. Also correlated with the confocal images is the ease with which cellular features can be distinguished: the images from the Au preparation all have a very strong homogenous background, making it harder to discern the features, and in general the cellular features of the 1–2Au more easily distinguishable than those of the 2Au.

To quantify the amount of scattering increase, the sum of squares of the values of each voxel was tabulated for each OCM image. The mean and standard error of all the images from a given preparation were then calculated; those results are shown in Figure 5.3. The increase in scattering in all three gold-labeled samples is shown quantitatively by comparing their sum of voxel values squared to that of the unlabeled cells. Among the gold-labeled samples themselves, the amount of scattering increase was the opposite of expected: the Au had the most scattering, then 2Au, then 1–2Au. However, the 2Au and 1–2Au samples are statistically indistinguishable.

The high amount of nonspecific binding was puzzling, and two hypotheses were put forth to explain the results of the labeling experiment. One possibility is that all of the spheres, especially the naked Au, bound to the cells via van der Waals forces. Because the naked Au has no dielectric material (protein) separating it from whatever surface it comes in contact

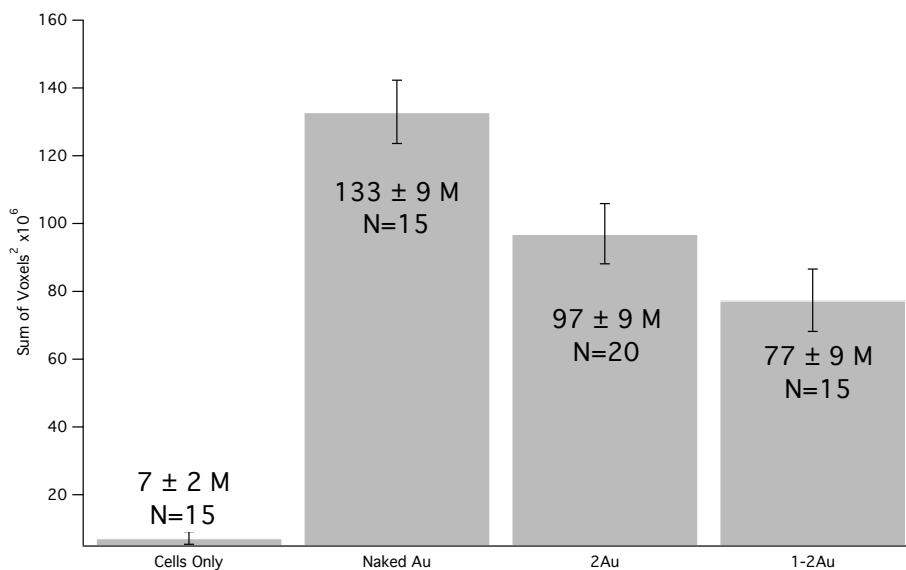


Figure 5.3 Sum of OCM voxel values squared for gold-labeled preparations and unlabeled cells; the sum of voxel values squared is a measure of the amount of backscattering from the field of view. Values are formed by taking the mean and standard error of sum of voxel values squared for each image corresponding to a given preparation.

with, the strength of van der Waals forces will likely be much larger for the naked Au than for the 2Au. The second possibility concerns the use of Triton-X, a permeabilizing agent. Triton-X is used to permeabilize the cells so that the Sytox Green and phalloidin stains can diffuse inside the cell and stain the nucleus and actin cytoskeleton, respectively. As a result, it was possible that the pores created by permeabilization of the cells allowed Au and 2Au to diffuse into the cell, but once in the cell, the gold nanospheres could not be removed by the washing process, leading to nonspecific contrast enhancement from nanoparticles inside the cell rather than on its surface. Furthermore, noting the strong background in some of the OCM images, there was some concern regarding the binding of the nanospheres to the coverslip surface itself. These concerns (van der Waals, permeabilization, and coverslip binding) led to a second round of immunolabeling experiments being performed on 3 April.

Chapter 6

Results of the 3 April Labeling Session

Given the puzzling results of the immunolabeling experiment performed on 6 March, a second immunolabeling experiment was carried out to answer two lingering questions: 1. Do the naked Au spheres and fully labeled spheres generate nonspecific contrast enhancement by binding to the coverslip? 2. Does permeabilizing the cells with Triton-X so that the cells can be stained with Sytox Green and phalloidin allow the gold nanospheres to diffuse into, but not out of, the cells, leading to nonspecific contrast enhancement? To address these questions, the gold-labeled preparations from the previous experiments were repeated without permeabilization and two new preparations were added, consisting of coverslips without cells and with gold labeling agents.

6.1 Structure of the Immunolabeling Experiment

6 preparations and their expected outcomes are described in Table 6.1. The labeling procedure was changed to remove the permeabilization (and the fluorescent stains, as they cannot label without the permeabilization). Full details are in Appendix C, but in brief, the procedure was:

1. Fix cells with paraformaldehyde
2. Add primary antibody if appropriate for a given preparation
3. Add appropriate secondary labeler

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Since the permeabilization was removed, the Sytox Green and phalloidin cannot label the intracellular structures; as a result the only fluorescence contrast would come from the AP124F. The permeabilization concerns were specific to the 2Au-labeled preparations, so no confocal fluorescence imaging was performed, only OCM imaging, again using $5\text{ }\mu\text{m} \times 500\text{ }\mu\text{m}$ fields of view.

Table 6.1 Description of the six preparations used in the 3 April immunolabeling experiment; each preparation is described by whether the primary antibody (MAB1999) was added, what secondary labeler (AP124F PEGylated to Au nanospheres or naked Au nanospheres) was added, and whether or not an increase was expected in backscattering.

Preparation Name	Primary Antibody?	Secondary Labeler?	+Scattering Expected?
Cells Only	No	No	No
Au	No	Naked Au	Yes
2Au	No	OPAb-Au-PS	No
1-2Au	Yes	OPAb-Au-PS	Yes
Coverslip-Au	No	Naked Au	Yes
Coverslip-2Au	No	OPAb-Au-PS	No

The results for the cells only sample should be the same as in the 6 March experiment. If permeabilization is causing gold spheres to become trapped in the cells, the voxels occupied by cellular material in the Au, 2Au, or 1-2Au samples should scatter less than the equivalent voxels for the permeabilized cells. As for the coverslips, the protein and PEG coating on the 2Au should prevent it from binding to the coverslip, resulting in very low scattering. Given the results from 6 March, the naked Au is expected to bind quite strongly to the coverslip via van der Waals forces, resulting in high scattering.

6.2 Results of the Immunolabeling Experiment

Representative images from the OCM are shown in Figure 6.1. There is a marked difference between the permeabilized and non-permeabilized preparations for the 1-2Au and 2Au preparations. First, cellular features are much more easily distinguished. This is likely due to the fact that the

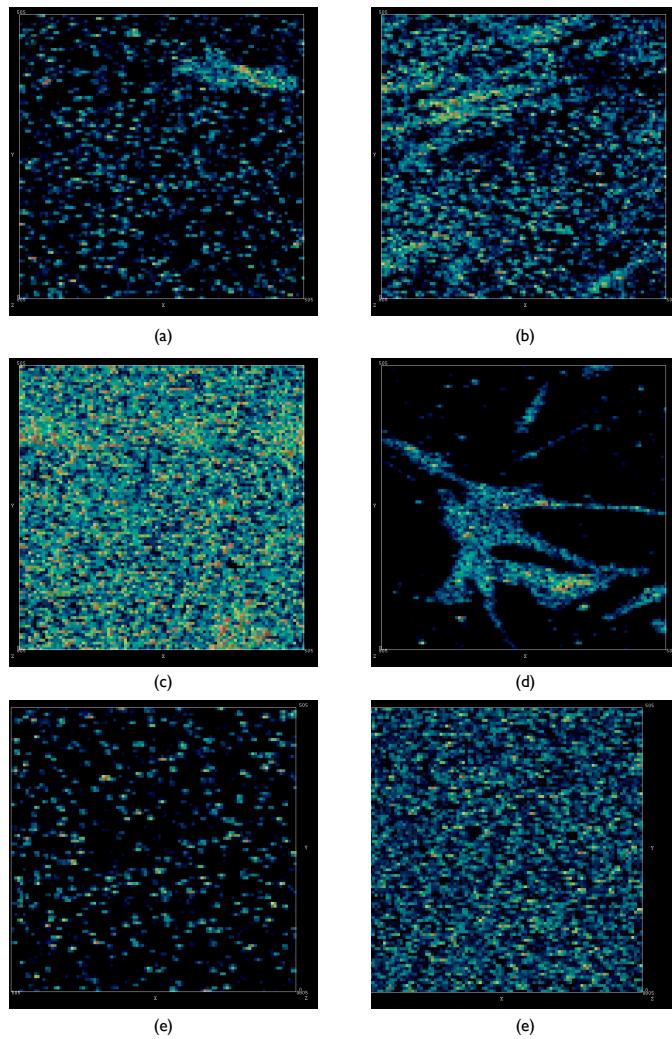


Figure 6.1 Representative OCM images of the 6 preparations from the 3 April immunolabeling session. Images correspond to preparations: (a) 1–2Au; (b) 2Au; (c) Au; (d) Cells only; (e) Coverslip–2Au; (f) Coverslip-Au.

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cells were allowed to grow on the coverslips for a shorter period than the previous set of cells, leading to a lower level of cell coverage and thus keeping most cells isolated. This lower cell density is harder to observe in the naked Au image due to the high amount of background from the Au nanospheres binding to the coverslip. The coverslip binding is demonstrated directly by the Coverslip-Au preparation: the binding is fairly homogenous and quite high. The Coverslip-2Au preparation also shows some scatterers present in the volume, though far fewer than the Coverslip-Au preparation. This is further evidence of the successful protection of the gold nanospheres by the PEG-SH and OPAb.

The same sum-of-voxels-squared analysis method was used on this set of images; a chart of those values is in Figure 6.2. There is again clear contrast enhancement and again the naked-Au-labeled cells are quite far above the rest of the samples. This time, however, the scattering from the 2Au-labeled cells is greater than the scattering from the 1-2Au-labeled cells in a statistically significant manner. This is exceptionally puzzling, as it suggests that the presence of primary antibody *decreases* the amount of non-specific binding quite considerably, either in conjunction with or instead of increasing the amount of specific binding. Clearly, more work must be done to understand this phenomenon.

Determining whether or not the permeabilization had an effect is something of a difficult business. Since the cells were at different stages of confluence, the two immunolabeling sessions cannot be compared directly. Rather, some normalization must take into account the different amount of cell coverage. It is not sufficient to simply divide by the scattering from the cells, as that ignores the binding of the spheres to the coverslip. Rather, let us approximate the coverslip and cells as a 2D grid, each pixel of which is either occupied completely by cell or completely by coverslip. Each pixel then contributes, on average, some amount of scattering depending on whether it is cell or coverslip; this amount is determined both by binding affinity and the scattering cross section of the scatterer. The sum of voxels squared, S_{voxels^2} can then be determined on average as a function of the fraction F of the viewing region covered by cell as

$$S_{\text{voxels}^2} = S_{\text{Coverslip}}(1 - F) + S_{\text{Cell}}F$$

where $C_{\text{Coverslip}}$ and C_{Cell} are the scattering from a view filled by coverslip or cellular materials labeled with the secondary labeler in question, respectively. We can determine $C_{\text{Coverslip}}$ from the coverslip binding sum of voxels squared; since they are taken at $F = 0$, $S_{\text{voxels}^2} = C_{\text{Coverslip}}$.

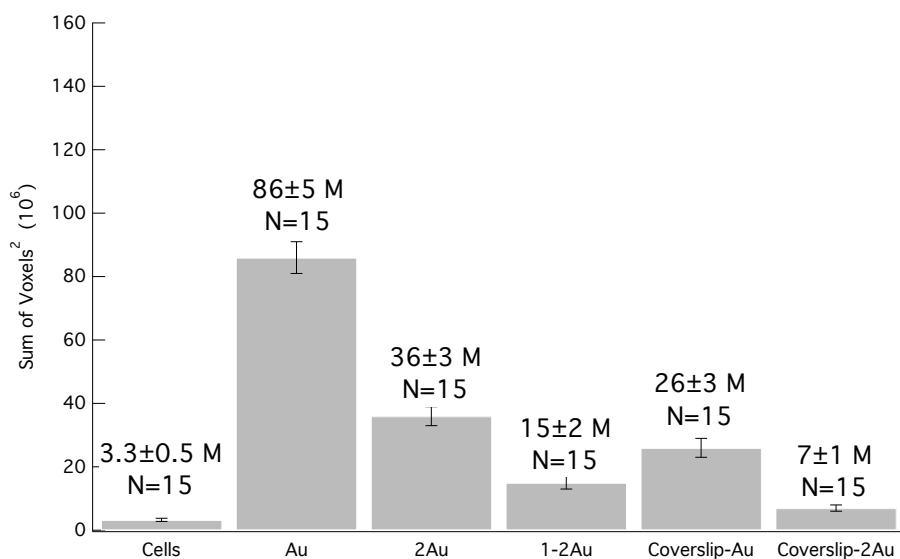


Figure 6.2 Plot of the mean of the sum of voxel values squared for all preparations. Values are formed by taking the mean and standard error of sum of voxel values squared for each image corresponding to a given preparation.

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From Figure 6.2, $C_{\text{Coverslip, Au}} = 2.6 \pm 0.3 \times 10^7$ and $C_{\text{Coverslip, 2Au}} = 7 \pm 1 \times 10^6$. To determine whether or not reducing the permeabilization had an effect, we need to determine C_{Cell} for Au and 2Au. We now see that we cannot simply divide by the scattering of the cells, which is $S_{\text{Cells Only}} = C_{\text{Cell, No Label}} F$, because that would give

$$S_{\text{norm}} = \frac{C_{\text{Coverslip}}(1/F - 1) + C_{\text{Cell}}}{C_{\text{Cell, No Label}}}$$

which still has F dependence. However, if we first normalize by subtracting $C_{\text{coverslip}}$, we get

$$S_{\text{norm}} = \frac{S_{\text{voxels}^2} - C_{\text{Coverslip}}}{S_{\text{Cells Only}}} = \frac{-C_{\text{Coverslip}} + C_{\text{Cell}}}{C_{\text{Cell, No Label}}} \quad (6.1)$$

This is sufficient to perform comparisons between the two immunolabeling sessions, as it does not depend on F at all; C_{Cell} could be calculated with sufficient image analysis, but generating a large enough dataset to adequately calculate it is beyond the scope of the studies performed. The results of performing this normalization are shown in Figure 6.3. For the naked Au the difference is actually the opposite of expected: the permeabilization decreases the amount of scattering per cell coverage; however, the uncertainties on this calculation are quite large, and consequently the difference is statistically consistent with 0. The same hold for the 2Au preparation, though the uncertainties are somewhat smaller and it shows the expected decrease. 1–2Au is the only preparation with a statistically significant difference, and the difference is quite large. Therefore, though there is a large amount of statistical uncertainty, permeabilization does appear to reduce the amount of scattering, which implies that gold spheres are getting inside of the cells. As this is undesirable, and the OCM imaging does not benefit from the fluorescent stains, permeabilization should not be used in future immunolabeling experiments.

As for van der Waals binding, both the Coverslip-Au and the Coverslip-2Au preparations indicate that van der Waals interactions are occurring between the coverslip and the gold, even when it's well-protected by the PEG. Furthermore, there must be strong van der Waals interactions occurring between the cell and the 2Au; though some non-specificity of the secondary antibody is expected, the extent to which the unpermeabilized 2Au preparation displays nonspecific binding to the cell is too large to simply be explained by poor localization of the protein. The high polarizability of the gold creates the potential for strong van der Waals forces, and it may

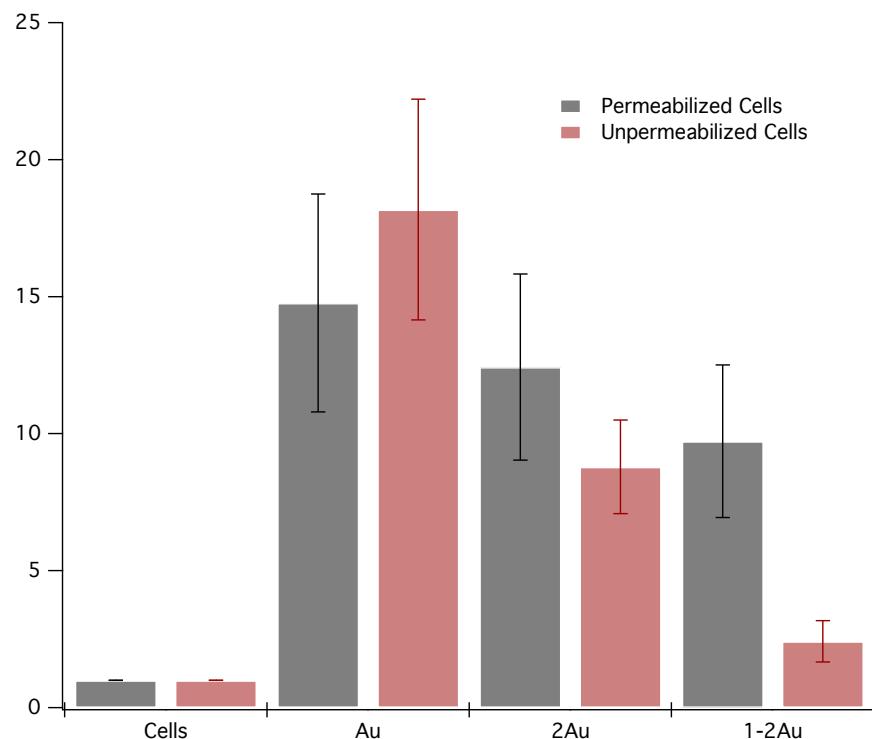


Figure 6.3 Sum of voxel values squared for gold-labeled preparations and cells, normalized using Equation 6.1.

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be the case that despite the ~7nm dielectric coating, a strong dipole can be induced in the gold.

Chapter 7

Conclusions and Future Work

Although the labeling experiments did not produce the hoped-for results of cellularly specific labeling, much progress has been made since the work of Perry Ellis and Oliver Hoidn in the summer of 2010. The PEGylation protocol has been completely optimized, and the spheres seem to be completely protected. In addition, it has been established that permeabilization permits Au nanoparticles to enter the cells, leading to an increase in non-specific binding.

There are also a number of new and unanswered questions. Most obvious of these is determining why the 2Au preparation experiences greater binding than the 1–2Au preparation. There are two factors that determine the binding: the van der Waals binding, and the specific binding of the secondary antibody to the primary antibody. The van der Waals binding can be calculated numerically if the spheres are modeled as a conducting core with a dielectric shell in a DC electric field; even without performing the calculations, it is obvious that the 35 nm diameter nanospheres used by the originators of this project would generate far smaller van der Waals forces. Consequently, use of smaller nanospheres may be necessary to reduce the van der Waals binding. The specific binding, to date, has only been measured by the addition of 2Au to primary-labeled cells. However, there is an alternative method by which this could be measured. If OPAb-Au-PS spheres were to be made using the primary antibody (OPAb1-Au-PS) instead of the secondary (OPAb2-Au-PS), then a DLS measurement performed on a mixture of OPAb1-Au-PS and OPAb2-Au-PS should show the spheres agglomerating and precipitating out of solution as the primary- and secondary-labeled spheres form a lattice of sorts. The rate at which this occurs and the final state of the solution should give an approximate

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measure of the binding strength between the secondary and primary antibodies. It may be the case that the 45 minutes allotted to the 2Au to bind to the primary-labeled integrins is too short to allow for a significant amount of binding; a longer binding period could be used to increase the scattering increase from the 1–2Au preparation. However, this would not explain the large amount of nonspecific binding observed in the 2Au sample; additional investigation of that phenomenon is clearly necessary.

Appendix A

The PEGylation Protocol

1. Create or obtain phosphate buffered Milli-Q (PBM-Q), at least 500 mL.
 - (a) Based on the work of Ellis and Hoidn [3], the salt concentration of the solution should be 10 mM with a pH of 7.6.
 - (b) To make 500 mL PBM-Q, combine 130 mg $\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$, 1090 mg $\text{Na}_2\text{HPO}_4 \cdot 7\text{H}_2\text{O}$, and 500 mL Milli-Q in a 500 mL sealable bottle. The Milli-Q should be measured out in a graduated cylinder.
2. Next, bind the OPSS-PEG-NHS (OPN) to the antibody (Ab). We want approximately a 2:1 ratio of OPN:Ab. The number concentration of the Ab is

$$\frac{8.92 \times 10^{15} \# \text{Ab}}{\text{mL}} = \left(2 \frac{\text{mg}}{\text{mL}} \right) \left(\frac{6.02 \times 10^{23} \# \text{Ab}}{135\text{kg}} \right).$$

Measuring a quantity less than 1 mg of OPN is quite difficult, and we want to use a minimum pipette volume of 5 μL . Therefore, we will use 6 mg of OPN in 200 mL of PBM-Q. This gives a solution with

$$\frac{8.6 \times 10^{15} \# \text{OPN}}{\text{mL}} = \left(6/200 \frac{\text{mg}}{\text{mL}} \right) \left(\frac{6.02 \times 10^{23} \# \text{Ab}}{2.1\text{kg}} \right).$$

Then, we combine 62.5 μL PBM-Q, 12.5 μL Ab, and 25 μL OPN+PBM-Q solution. Since the concentration of the Ab and OPN are approximately the same, and the volume used of the OPN+PBM-Q solution is double that of the Ab, there should be approximately a 2:1 OPN:Ab ratio. The actual procedure should be as follows:

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- (a) Fill insulated container with ice.
 - (b) In a 1.5 mL centrifuge tube, combine 62.5 μL PBM-Q and 12.5 μL Ab. Put tube in ice.
 - (c) Measure out 200 mL PBM-Q and put in a sealable 250 mL bottle.
 - (d) Measure out 6 mg OPN and add it to the 200 mL PBM-Q.
 - (e) Quickly add 25 μL OPN+PBM-Q solution to the centrifuge tube, to minimize hydrolysis of the NHS ester.
 - (f) Wait 24 hours for complete binding.
3. Next, bind the OPAb to the Au nanospheres. We want 2000 OPAb/Au, and we want 500 mL of labeled spheres. The OPAb concentration is $1.1 \times 10^{15} \frac{\#OPAb}{\text{mL}}$; therefore, we need

$$(500 \mu\text{L} Au) \left(5 \times 10^9 \frac{\text{Au}}{\text{mL}} \right) \left(2000 \frac{\text{OPAb}}{\text{Au}} \right) / \left(1.1 \times 10^{15} \frac{\#OPAb}{\text{mL}} \right) = 4.5 \mu\text{L OPAb.}$$

The procedure for this step is:

- (a) pH-correct/buffer Au solution:
 - i. Centrifuge 500 μL Au at 4200 RPM with soft brake for 10 minutes in a 5417C centrifuge.
 - ii. Remove 2/3 of the supernatant (333 μL) and replace with PBM-Q, making sure to resuspend the Au solution very well.
 - (b) Add 4.5 μL OPAb solution made the previous day to the Au solution.
 - (c) Immediately DLS 50 μL of the OPAb-Au solution.
 - (d) Wait 24 hours for OPAb-Au reaction to complete; again, DLS 50 μL .
4. The final step of nanoparticle assembly is to add 5 kDa PEG-SH to the OPAb-Au. We want 10000 PEG-SH/Au for the 400 mL of remaining OPAb-Au solution.

- (a) First, make a PEG-SH+PBM-Q solution. 300 mL PBM-Q and 10 mg 5 kDa PEG-SH gives

$$\frac{4 \times 10^{15} \#PS}{\text{mL}} = \left(10/300 \frac{\text{mg}}{\text{mL}} \right) \left(\frac{6.02 \times 10^{23} \#Ab}{5\text{kg}} \right).$$

(b) To get 10,000 PS/Au, we add

$$(400\mu\text{L OPAb - Au}) \left(5 \times 10^9 \frac{\text{OPAb - Au}}{\text{mL}} \right) \left(10000 \frac{\text{PS}}{\text{OPAb - Au}} \right) / \left(4 \times 10^{15} \frac{\# \text{PS}}{\text{mL}} \right) = 5\mu\text{L PS}$$

to the 400 μL OPAb-solution.

- (c) DLS 50 μL OPAb-Au-PS immediately.
 - (d) Wait 24 hours; DLS 50 μL OPAb-Au-PS.
5. A final, optional step is to check the protection of the fully labeled and protected nanospheres. To do this, obtain a new centrifuge tube and put at least equal volumes (at least 50 μL) of both OPAb-Au-PS solution and commercial PBS solution. DLS 50 μL . Radius should be stable if the spheres are protected.

Appendix B

The 6 March Immunolabeling Protocol

Action	Volume	Time
Make 10% goat serum in PBS		
Remove media from samples		
Cover cells with PBS	500 μ L	
Fix cells in 4% Paraformaldehyde (dilute 16% stock in 1x PBS), shaking, in hood	1 mL	10 min
Rinse cells with Milli-Q water	500 μ L	2x10 min
Permeabilize cells in 0.1% Triton-X (diluted with Milli-Q water)	500 μ L	15 min
Rinse wells with Milli-Q water twice	500 μ L	2 x
Incubate with mixture of nuclear stain (Sytox Green 1:2000 dilution) and f-actin stain (rhodamine phalloidin 1:40) diluted in 10% goat serum at RT in the dark	500 μ L	45 min
Wash with 10% goat serum in the dark	500 μ L	3x5 min
Label samples with 1:100 Diluted MAB1999 (primary Ab), leave all other samples in goat serum	500 μ L	45 min
Wash in 10% goat serum	500 μ L	3x5 min
Label relevant samples with undiluted 2-Au, naked Au (or not)	500 μ L	45 min
Wash in 10% goat serum	500 μ L	3x5 min
Leave all other samples in goat serum		
Rinse with PBS	1 mL	1x

Appendix C

The 3 April Immunolabeling Protocol

Action	Volume	Time
Make 10% goat serum in PBS		
Remove media from samples		
Cover cells with PBS	500 μ L	1 x
Fix cells in 4% Paraformaldehyde (dilute 16% stock in 1x PBS), shaking, in hood	1 mL	10 min
Rinse cells with Milli-Q water, shaker	500 μ L	2x10 min
Wash with 10% goat serum in the dark	500 μ L	45 min
*Label samples with 1:100 Diluted MAB1999 (primary Ab), leave all other samples in goat serum	500 μ L	45 min
Wash in 10% goat serum	500 μ L	3x5 min
*Label relevant samples with undiluted 2-Au, naked Au (or not)	500 μ L	45 min
Wash in 10% goat serum	500 μ L	3x5 min
*Leave all other samples in goat serum		
Rinse with PBS	1 mL	1x

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