BIOMATERIALS

The Intersection of Biology and Materials Science

Solution Manual

J. S. Temenoff | A. G. Mikos

Preface and Acknowledgments

This solution manual is an accompaniment to *Biomaterials: The Intersection of Biology and Materials Science* by J.S. Temenoff and A.G. Mikos (Pearson Prentice Hall, Upper Saddle River, 2008) intended for educators only. It contains the end-of-chapter problems written in this textbook and their solutions. It is important to indicate that the answers to the problems were formulated taking into consideration the material covered up to that point in the textbook.

We would like to express our gratitude to the following two individuals for their valuable assistance in the preparation of the solution manual: Mark Sweigart, Ph.D. (Rice University), who wrote the end-of-chapter problems and prepared the first draft of their solutions, and Leda Klouda, M.S. (Rice University), who contributed to the solutions of the problems and edited the manual to its final version.

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J.S. Temenoff

A.G. Mikos

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Chapter 1

1.1 One common biomaterial application is the construction of an arterial graft, a device that replaces a section of an artery. An artery is a flexible blood vessel that can withstand varying pressures and regulates the flow of blood. Arteries also provide a smooth interior surface to inhibit blood clotting within the vessel.

a. You need to design a vascular graft. List some advantages and disadvantages with each of the three major types of biomaterials. Which would you choose for this application?

Answer:

	Advantage	***Disadvantage***
Ceramics	*Strong*	*Rigid* *Brittle*
Metals	*Strong* *Easy to shape* *Inexpensive and available*	*Inflexible*
Polymers	*Can be flexible, smooth*	

A polymer would be more suitable for the vascular graft application, since neither metals nor ceramics offer the necessary elasticity.

b. What specific material characteristics need to be considered for the arterial graft application?

Answer: Flexibility is very important, and the material should also possess a certain tensile strength. The surface properties of the material like smoothness and hydrophobicity must be also considered in terms of its ability to support adhesion of endothelial cells or not cause damage to platelets. Moreover, the material should be easy to shape.

c. Would you use a natural or synthetic material for this application? What are the advantages and disadvantages of each?

Answer: A natural polymer would be more likely to integrate into the surrounding tissue. However, natural polymers may not possess the necessary mechanical properties for this application. There is also the possibility of evoking an immune response or a pathogen transmission. Synthetic polymers could be manufactured to have the necessary mechanical properties but may not integrate well with native tissue. Either natural or synthetic material is acceptable with proper justification.

1.2 Various biomaterials can be used for joint replacement applications, such as hip implants (see Fig. 1.4). A hip joint replacement must withstand large forces (standing on one leg results in a load of 2.4 times body weight on the femoral head [19]; jumping and running generate higher forces) normally transferred through the hip joint. It must also allow for proper rotation of the joint.

a. Which of the three major types of biomaterials would you use for the femoral stem? Why?

Answer: Metals and ceramics both may be present in the stem of a hip replacement. Metals are typically used in the core of the stem because of their strength and because they are easily molded into complex shapes. Ceramics may be used on the surface of the stem to facilitate integration with the bone.

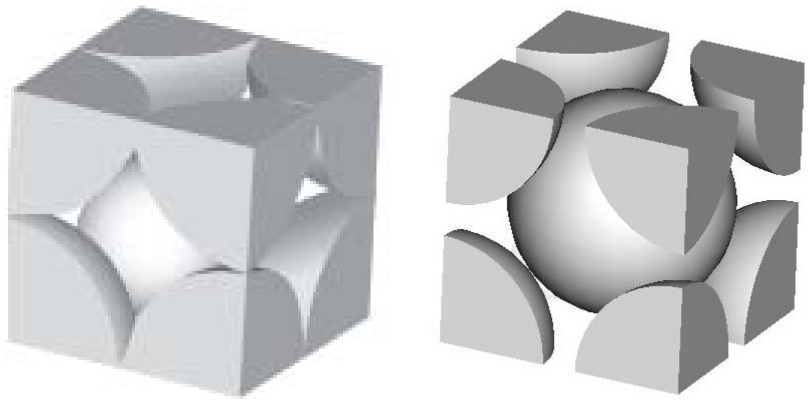
b. Would integration of the femoral stem with the surrounding tissue be an acceptable biological response? Why or why not?

Answer: Integration of the stem with the surrounding bone would be desirable, as it would better fix the implant into the surrounding tissue. Integration at the joint space would be undesirable, as it could impair movement.

Chapter 2

2.1. You are evaluating a variety of new materials for use in the femoral stem of a hip joint replacement.

a. Diagrams of the crystal structures of materials (a) and (b) are shown below. Identify each crystal structure. For each structure calculate the coordination number, derive the relation between *r* (radius of sphere) and *a* (length of cube side), and determine the APF of each.



(a) (b)

Answer: (a) is a simple cubic unit, and (b) is a body centered cubic.

(a): Coordination number is 6 (number of nearest neighbor atoms).
r/a relation: $\boxed{a = 2r}$ *(determined by examining edge of cube)*

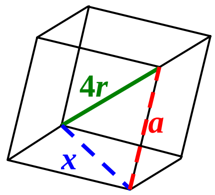
$$APF = \frac{Volume\ of\ atoms\ in\ unit\ cell}{unit\ cell\ volume}$$

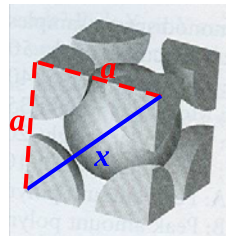
The number of atoms in the unit cell is 1($8x\frac{1}{8}$*), therefore the volume is* $\frac{4}{3}\pi r^3$

Unit cell volume is $a^3 = 8r^3$

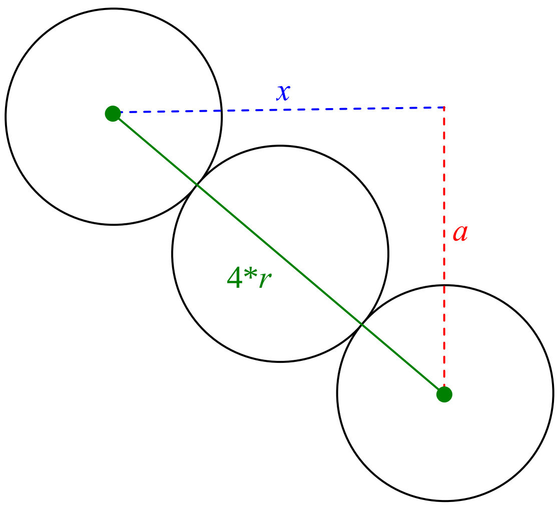
Therefore: $\boxed{APF = \frac{\frac{4}{3}\pi r^3}{8r^3} = \frac{\pi}{6} \cong 0.52}$

(b): Coordination number is 8.
r/a relation: Make a triangle that consists of an edge of the cube, a diagonal along the face of the cube, and a diagonal through the cube. The dimension of the edge is a*, the dimension of the diagonal through the cube is* 4r*, and the diagonal through the face (*x*) needs to be calculated. To do this, make another triangle on the face of the cube, with 2 sides being* a*, and the diagonal being equal to what we are looking for (*x*). Using Pythagorean Theorem, this can be calculated:*

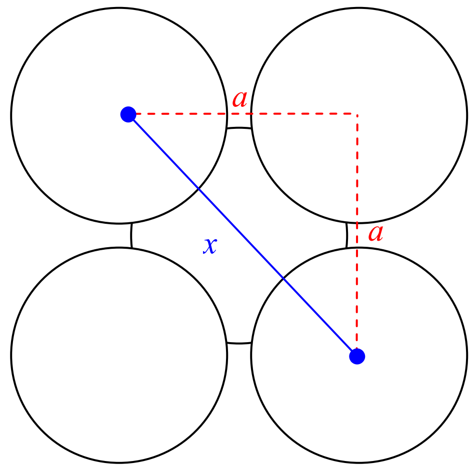




Diagonal:



Side:



$a^2 + a^2 = x^2$

$x = a\sqrt{2}$

Now use Pythagorean Theorem again on the initial triangle.

$a^2 + \left(a\sqrt{2}\right)^2 = (4r)^2$

$a^2 + 2a^2 = 16r^2$

$3a^2 = 16r^2$

$$\boxed{a = \frac{4r}{\sqrt{3}}}$$

$$APF = \frac{Volume\ of\ atoms\ in\ unit\ cell}{unit\ cell\ volume}$$

The number of atoms in the unit cell is 2, therefore the volume is: $2\left(\frac{4}{3}\pi r^3\right)$

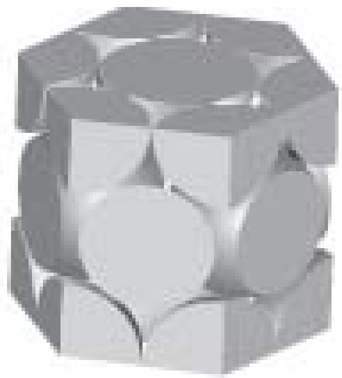
Unit cell volume is $a^3 = \frac{(4r)^3}{\sqrt{3}^3}$

Therefore: $\boxed{APF = \frac{\frac{8}{3}\pi r^3}{\frac{64r^3}{3\sqrt{3}}} = \frac{\pi\sqrt{3}}{8} \cong 0.68}$

b. You are given a third material (c), which has not been characterized. What analytical technique would you use to determine the crystal structure and unit cell size?

Answer: X-ray diffraction can determine these material characteristics.

c. You determine that material (c) has a hexagonal close-packed structure, which is shown below. Calculate the APF of this material. The *c*-to-*a* ratio is 1.633, where c is the height and a is the length of each side. (Note: the center layer consists of the equivalent of three total atoms within the unit cell, and the radius of the atom is *r*).



(c)

Answer:

$$APF = \frac{Volume\ of\ atoms\, in\, unit\, cell}{unit\, cell\, volume}$$

The number of atoms in the unit cell is 6, therefore the volume is: $6\left(\frac{4}{3}\pi r^3\right)$

*To calculate the unit cell volume, find the area of the hexagon, and multiply by the height (*c*).*

The area of a hexagon is $\frac{3}{2}a^2 \cot\frac{\pi}{6} = \frac{3\sqrt{3}}{2}a^2$

and since we know c=1.633a*, the volume of the unit cell is* $1.633\frac{3\sqrt{3}}{2}a^3$

and a=2r

Therefore: $\boxed{APF = \frac{8\pi r^3}{1.633\left(12\sqrt{3}\right) r^3} \cong 0.74}$

d. Would you be likely to find interstitial defects in any of these three materials? Why?

Answer: It is unlikely to find interstitial defects in structures with large atom size and small spacing between the atoms. The closer the packing, the fewer the defects. Therefore, if interstitial defects were to occur, they would most likely be found in the simple cubic unit structure, which has the lowest APF.

2.2 You are examining a copolymer for its potential as a material for a vascular graft. You are trying to determine whether you want a high or low degree of crystallinity in the material. What type of structures for copolymers have a higher probability for crystallization?

Answer: Alternating and block copolymers have a higher affinity for crystallization. The repeatability of the structure induces the formation of order. Random and graft copolymers have a lower affinity for crystallization. The random structure may not allow for crystallization, whereas the graft structure is inclined to hinder secondary interactions between the chains.

2.3 Poly(ε-caprolactone) is being considered as a potential material for a vascular graft. After a particular batch has been made, someone gives you the following fractional distribution data and asks you to calculate $\overline{M}_n$, $\overline{M}_w$ and PI for this polymer.

W_i	0.10	0.10	0.30	0.40	0.10
M_i (kg/mol)	25	30	40	70	100

Answer: Use the following equations to generate the numbers in the table below:

$N_i = W_i / M_i$ $\qquad$ $x_i = N_i / \sum N_i$ $\qquad$ $w_i = W_i / \sum W_i$

W_i	***0.10***	***0.10***	***0.30***	***0.40***	***0.10***
M_i (kg/mol)	***25***	***30***	***40***	***70***	***100***
N_i	*0.004*	*0.003*	*0.008*	*0.006*	*0.001*
x_i	*0.18564*	*0.15470*	*0.34807*	*0.26519*	*0.04641*
x_iM_i	*4.64088*	*4.64088*	*13.92265*	*18.56354*	*4.64088*
w_i	*0.1*	*0.1*	*0.3*	*0.4*	*0.1*
w_iM_i	*2.5*	*3*	*12*	*28*	*10*

$\overline{M}_n = \sum_i x_i M_i = 46.41$ kg/mol

$\overline{M}_w = \sum_i w_i M_i = 55.5$ kg/mol

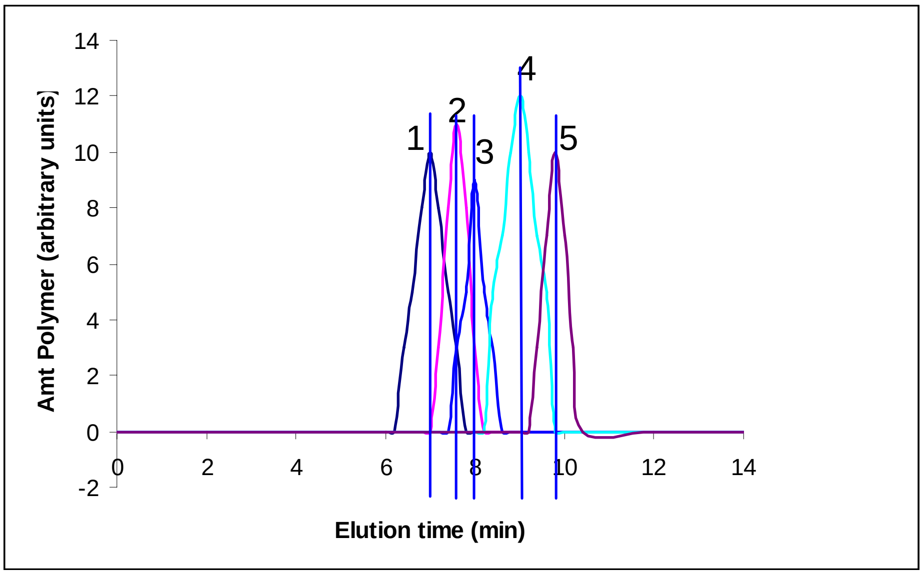
$PI = \overline{M}_w / \overline{M}_n = 1.20$

2.4 You are given four additional polymeric materials (A, B, C, D) to examine for potential as a vascular graft material, and are told to use size-exclusion chromatography to determine the approximate molecular weights of the unknown polymers. You obtain the following information for the first three samples (A, B, C).

a. Assuming monodisperse samples, what is the molecular weight of each?

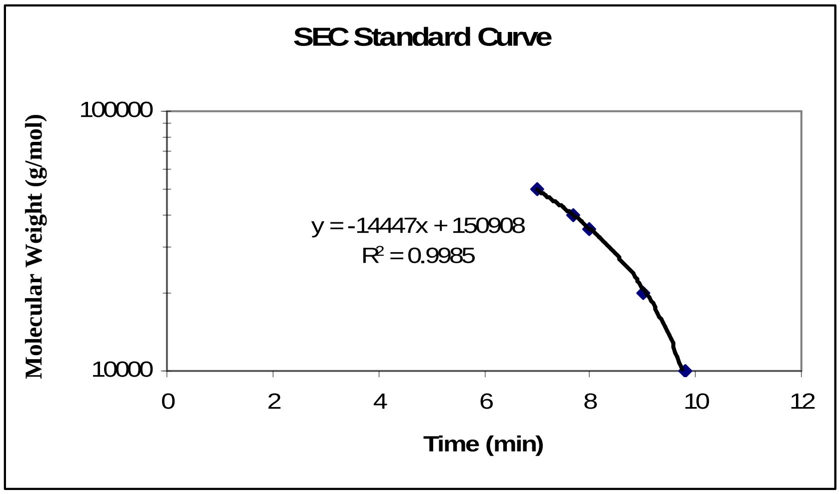
Standard 1: Molecular weight 50,000 g/mol
Standard 2: Molecular weight 40,000 g/mol
Standard 3: Molecular weight 35,000 g/mol
Standard 4: Molecular weight 20,000 g/mol
Standard 5: Molecular weight 10,000 g/mol
Unknown A: Peak amount polymer eluted at 7.4 min
Unknown B: Peak amount polymer eluted at 8.4 min
Unknown C: Peak amount polymer eluted at 9.6 min

Answer: See Figure 2.57 in the book.



Std #1: Molecular wt. 50,000 g/mol approx. elution time: 7.0 min.
Std #2: Molecular wt. 40,000 g/mol approx. elution time: 7.7 min.
Std #3: Molecular wt. 35,000 g/mol approx. elution time: 8.0 min.
Std #4: Molecular wt. 20,000 g/mol approx. elution time: 9.0 min.
Std #5: Molecular wt. 10,000 g/mol approx. elution time: 9.8 min.

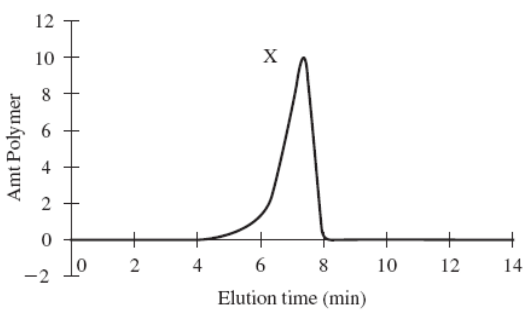
Now create a standard curve:

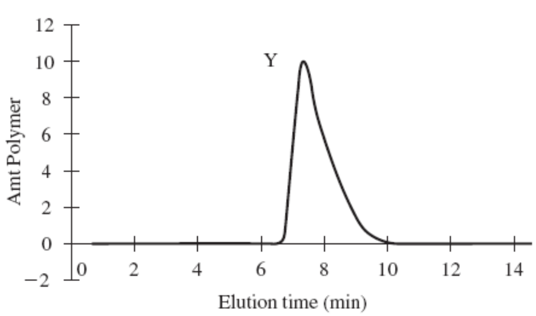


Use the equation from the standard curve to estimate the molecular weight.

Unknown A: Peak amount polymer eluted at 7.4 min *MW ~ 44,000 g/mol*
Unknown B: Peak amount polymer eluted at 8.4 min *MW ~ 29,500 g/mol*
Unknown C: Peak amount polymer eluted at 9.6 min *MW ~ 12,200 g/mol*

b. A problem commonly encountered in SEC is overloading the chromatography column by injection of a highly concentrated sample, which results in broadening of the peak on the chromatogram. You injected a highly concentrated sample of unknown D into the chromatography column. Which of the following curves would result? Pick X or Y and describe why, based on molecular interactions of the sample with the column.



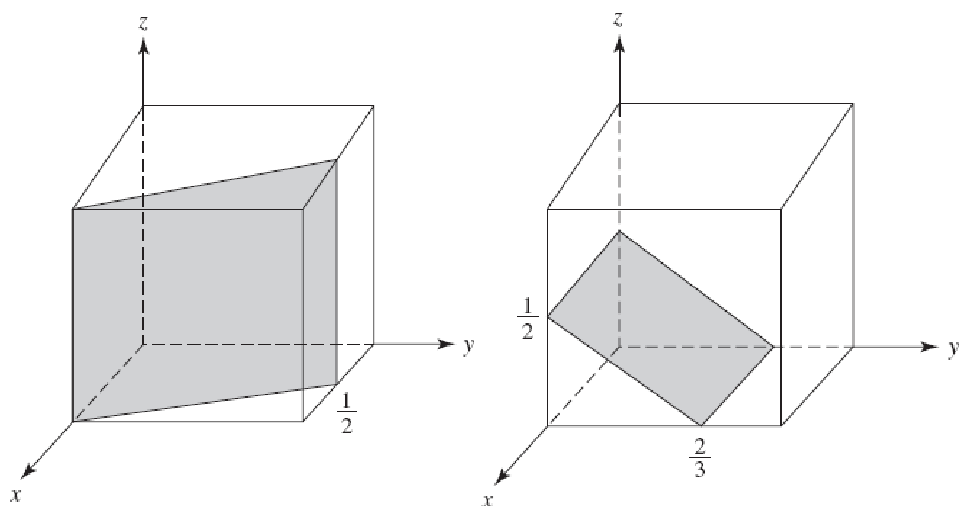


Answer: Either X or Y is acceptable, as long as a reasonable, molecular-based reason was given.

In reality, Y occurs. This is because, if you add a sample that is highly concentrated, there will be more of both the larger and smaller molecular weight fractions of the sample. The smaller MW fractions will find their way into the pores of the packing material. Therefore, the smaller MW polymers that are in too high of a concentration in the pores act to "trap" each other in the pores and prolong their transition. A larger number of molecules take longer to be eluted than normal; the shoulder is found on the right of the peak.

However, the scenario depicted in X could be explained by the presence of aggregates which would act as high molecular weight (large size) polymers and would be eluted earlier from the column.

2.5 Calculate the Miller indices for the following planes and include the steps necessary to arrive at your conclusion. (Note: x = a axis, y = b axis, z = c axis)



(a) (b)

Answer:

		(x)	*(y)*	*(z)*
		a	*b*	*c*
plane A	*intercepts*	*1*	*2*	∞
	reciprocals	*1*	*1/2*	*0*
	multiplier	*x2*	*x2*	*x2*
	indices	*(2*	*1*	*0)*
plane B	*intercepts*	∞	*2/3*	*1/2*
	reciprocals	*0*	*3/2*	*2*
	multiplier	*x2*	*x2*	*x2*
	indices	*(0*	*3*	*4)*