



BIOMEDICAL
ENGINEERING

Carnegie Mellon University

42-648/24-612, Cardiovascular Mechanics
Carnegie Mellon University
Department of Biomedical Engineering
Spring 2016

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Note: Please use email, as I am usually out of my office.
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Class Time and Locations:

Lecture: 10:30 to 11:50 AM, Tuesday and Thursday
Recitation: 9:30 to 10:20, Friday
Room (for both): Scaife Hall 208

Textbook: Relevant reading materials are listed under each section in the course outline below. Most, but not all, of the course information is covered in this text:

Biofluid Mechanics: The Human Circulation, Second Edition (2012)
Krishnan B. Chandran, Stanley E. Rittgers and Ajit P. Yoganathan

Additional references will be either be posted on Blackboard or on reserve at the library. These are noted in the course outline. Of note, textbooks in cardiovascular physiology, fluid mechanics, and electrical circuit analysis will be helpful either to review or if you are missing courses in these areas.

Class Website: All registered students will have access to the class website via Blackboard (<http://www.cmu.edu/blackboard>). Class announcements, course information, instructor and teaching assistant information, course documents, and assignments are contained on this website. This website will be constantly updated with relevant information throughout the semester.

Prerequisites: A basic course in Fluid Mechanics.

Course Description and Objectives: The primary objective of the course is to teach how to model blood flow and mechanical forces in the cardiovascular system. After a brief review of cardiovascular physiology and fluid mechanics, the course will progress from modeling blood flow in a.) small-scale steady flow applications to b.) small-scale pulsatile applications to c.) large-scale or complex pulsatile flow applications. The course will also discuss how to calculate mechanical forces on cardiovascular tissue (blood vessels, the heart) and cardiovascular cells (endothelial cells, platelets, red and white blood cells), and the effects of those forces. Lastly, the course will teach various methods for modeling cardiac function. When applicable, we will discuss the application of these concepts to the design and function of selected medical devices (heart valves, ventricular assist devices, artificial lungs).

The outline, with reading materials, is described below.

1. Introduction to the course

2. Cardiovascular physiology review

Reading: Chandran 3.1-3.6, 3.8

Supplemental reading: Any cardiovascular physiology textbook from the last 15 years. I suggest Cardiovascular Physiology by Berne and Levy (the most recent, 10th edition of the same book is by Pappano and Wier). I will put my own copy of the 9th edition on reserve in the library (please be gentle with it), and it is also available from the University of Pittsburgh medical library.

3. Fluid mechanics review/intro to blood flow in tubes

Reading: Chandran 1.1.-1.2.2, 1.3, 1.4.1, 1.5.2-3

Supplemental reading: Any fluid dynamics textbook from the last 20 years as needed. Those by Robert W. Fox and Bruce R. Munson are recommended but many options exist in the library.

4. Blood rheology

Reading: I will lecture beyond Chandran, so the other reading will be helpful.

1. Chandran 4.1.2-4.1.3.7.

2. Whitmore, RL, Rheology of Circulation, pages 11-16.

3. Pries, Secomb, and Gaetgens, 1996, Biophysical aspects of blood flow in the microvasculature.

4. Merrill EW, 1969, Rheology of Blood, pages 874-877.

5. Pulsatile blood flow in solid tubes: Womersley's solution

Reading: Chandran 6.3.1.2

6. Vascular mechanics

Reading: Chandran 4.2.1, 4.2.2, 2.1-2.4, but I will lecture far beyond this.

7. Pulsatile blood flow modeling: lumped parameter models

Reading: None

Supplemental Reading: Circuit Analysis textbook, in particular sections on phasor analysis and circuit analysis of alternating currents.

8. Wave reflections

Reading: Nichols WM and O'Rourke MF, McDonald's Blood Flow in Arteries: Chapter 9, Wave Reflections, pages 251-254.

9. Cardiac mechanics

9.1: Cardiac Physiology Review

Reading: Cardiovascular physiology textbook (Berne and Levy, Ch 3, The Cardiac Pump).

9.2: Preload and Afterload

Reading:

1. Cardiovascular physiology textbook (Berne and Levy, Ch 3, The Cardiac Pump).
2. Katz AM, Physiology of the Heart, p. 130-135.
3. Leyton RA, Chapter 2: Cardiac Ultrastructure and Function in the Normal and Failing Heart, in Mirsky, Ghista, and Sandler, Cardiac Mechanics, 1974.

9.3a: Contractility

Reading: Cardiovascular physiology textbook (Berne and Levy, Ch 3, The Cardiac Pump)

9.3b: Models of Cardiac Function: single ventricle, end-systolic pressure volume relationship

Reading:

1. Berne and Levy, Ch 9, Control of Cardiac Output: Coupling of Heart and Blood Vessels.
2. Sunagawa and Sagawa, Models of ventricular contraction based on time-varying elastance, Critical Reviews in Biomedical Engineering 7, 193-228, 1982.
3. Sunagawa et al., Left ventricular interaction with arterial load studied in isolated canine ventricle, Am. J. Physiol. 245 (Heart Circ. Physiol. 14): H773-H780, 1983.

9.4: Work Based Models of Cardiac Function

Reading:

1. Glower et al., Linearity of the Frank-Starling relationship in the intact heart: the concept of preload recruitable stroke work, Circulation 71: 994-1009, 1985.
2. McClain et al. Afterload sensitivity of nonlinear end-systolic pressure-volume relation vs preload recruitable stroke work in conscious dogs. Journal of Surgical Research 75, 6-17, 1998.
3. (if time allows) Elbeery et al. Mechanical determinants of myocardial oxygen consumption in conscious dogs, Am. J. Physiol. 269 (Heart Circ. Physiol. 38): H609-H620, 1995.

10. Mechanotransduction: the effect of fluid mechanical forces on cardiovascular cells

Reading:

1. Chandran 8.3.4 intro, 3.10, 6.5
2. Malek, Alper, and Izumo: Hemodynamic Shear Stress and Its Role in Atherogenesis, JAMA 282, 2035-2042.

By the end of this course, the students should be able to do the following:

1. Understand the rheology of blood
2. Solve steady blood flow problems
3. Model pulsatile blood flow in devices and systems
4. Model stress and strain in blood vessels and heart tissue
5. Understand the effect of mechanical forces on various cardiovascular cells
6. Have a more detailed understanding of the biomechanics of ventricular preload, afterload, and contractility.
7. Model cardiac function under varying preload, afterload, and contractility using several different models.
8. Understand biomechanical issues in selected cardiovascular medical devices.

Lecture Notes: The lectures notes form the bulk of the class material and are not always replicated in your textbook or supplementary reading. The lectures notes will be made available on blackboard at least two days before each lecture. The lecture notes are living documents, however, and there is no guarantee that they will not change in small ways prior to the lecture.

Homework: Homework will typically be assigned on Tuesday via Blackboard and due the following Tuesday. However, I will adjust due dates depending on how well we are doing getting through and understanding the material. There will be approximately 9 homework assignments, and thus every week will not have homework.

Homework will be returned in paper form and must be submitted **prior to the beginning** of class on the day it is due. Homework solutions will be posted on the class website one week after the graded homework is returned and in some cases earlier to help with exam preparation. Any assignment turned in after the due date will be deducted 15 percentage points for every day it is late, including weekends. After one week, you will not be allowed to turn in that homework.

Exams: There will be two closed book exams and one final. For each, I will provide you with a formula sheet that contains all necessary formulas and unit conversions.

Recitation Section Presentations: During Friday recitation, we will discuss papers pertinent to this class. I will present first and students will present each class thereafter (schedule will be given to you in class). Each student is expected to present one 20-25 minute presentation during the semester. Each of us will introduce the class to a topic via an overview of one review paper (paper that broadly reviews a topic). The review paper must contain at least 20 references and must be from the last 10 years. Each student in the audience is expected to turn in a brief questionnaire on the presentation. All of these assignments will be dealt with on a check minus (80%), check (90%), or check plus level

(100%). Half of your recitation grade will be based on your presentation and half will be based on your questionnaires on the presentations.

A list of possible topics for the presentations is offered below, but *this is by no means exhaustive*. The only requirement is that the focus be on cardiovascular biomechanics. Please discuss other ideas with me.

1. Any of the topics outlined in the course syllabus: blood rheology, modeling of blood flows in the cardiovascular system, cardiac mechanics, etc.
2. Design, testing, and clinical use of blood-bearing artificial organs: ventricular assist devices, blood pumps in general, artificial lungs, artificial kidneys, artificial livers, vascular grafts, and heart valves.
3. Tissue engineered myocardium and vascular grafts
4. Congenital heart defects: their fluid mechanics, modeling, and repair.
5. The effect of mechanical forces on any cardiovascular cell type: red blood cells, platelets, white blood cells, endothelial cells, smooth muscle, myocytes, fibroblasts, etc.
6. Baroreceptor function and dysfunction.
7. Clinical and laboratory measurement of cardiovascular physiology: cardiac ultrasound/echocardiography, MRI, and PET; sonomicrometry; measurement of blood flow by Doppler or thermodilution; etc.
8. Cardiovascular surgical planning
9. The fluid and tissue mechanics of various cardiac malformations: aneurysms, fistulas, etc.
10. Biomechanical aspects of stem cells and stem cell differentiation in cardiovascular applications.
11. The biomechanics of ventricular contraction or coronary artery blood flow.

Grading

The final grade will be computed by combining homework, exams, and the project in the following manner.

Homework: 20%

Exam 1: 20%

Exam 2: 20%

Recitation: 15%

Final Exam: 25%

I tentatively planning on having the exams February 14th and March 24th.

The following scale will be used to assign a final letter grade*:

90 to 100%	A
80 to 89%	B
70 to 79%	C
60 to 69%	D
0 to 59%	R

**However, I will almost certainly curve your grades to improve them using a flat scale. That is I will add a fixed number of points to everyone's grade such that the average grade is increased to an 88% (B+) for graduate students. This is a graduate school class and thus, I do not expect many undergraduates. However, I reserve the right to grade the undergraduates on a separate curve.*

Other Class Policies

Attendance: Attendance at lectures is *highly recommended*. Although there is a text and a variety of recommended reading, much of the lecture material will be drawn from other sources. In addition, sample problems will be outlined in class that cannot be found in the reading.

Class Decorum: The use of cell phones during class is **prohibited**. Laptops may be used, but students must ask me specifically to be able to use them and the reason for using them must be stated (to take notes, for example).

Academic Integrity: (Excerpted from <http://www.cmu.edu/academic-integrity/index.html>)

Students at Carnegie Mellon, because they are members of an academic community dedicated to the achievement of excellence, are expected to meet the highest standards of personal, ethical and moral conduct possible.

These standards require personal integrity, a commitment to honesty without compromise, as well as truth without equivocation and a willingness to place the good of the community above the good of the self. Obligations once undertaken must be met, commitments kept.

As members of the Carnegie Mellon community, individuals are expected to uphold the standards of the community in addition to holding others accountable for said standards. It is rare that the life of a student in an academic community can be so private that it will not affect the community as a whole or that the above standards do not apply.

The discovery, advancement and communication of knowledge are not possible without a commitment to these standards. Creativity cannot exist without acknowledgment of the creativity of others. New knowledge cannot be developed without credit for prior knowledge. Without the ability to trust that these principles will be observed, an academic community cannot exist.

The commitment of its faculty, staff and students to these standards contributes to the high respect in which the Carnegie Mellon degree is held. Students must not destroy that respect by their failure to meet these standards. Students who cannot meet them should voluntarily withdraw from the university.

Cheating and Plagiarism: According to the [University Policy on Cheating and Plagiarism](#), “cheating includes but is not necessarily limited to:

- [Plagiarism](#) (see below).
- Submission of work that is not the student's own for papers, assignments or exams.
- Submission or use of falsified data.
- Theft of or unauthorized access to an exam.
- Use of an alternate, stand-in or proxy during an examination.
- Use of unauthorized material including textbooks, notes or computer programs in the preparation of an assignment or during an examination.
- Supplying or communicating in any way unauthorized information to another student for the preparation of an assignment or during an examination.
- Collaboration in the preparation of an assignment. [Unless specifically permitted or required by the instructor, collaboration will usually be viewed by the university as cheating.](#) Each student, therefore, is responsible for understanding the policies of the department offering any course as they refer to the amount of help and collaboration permitted in preparation of assignments.
- Submission of the same work for credit in two courses without obtaining the permission of the instructors beforehand.”

According to the [University Policy on Cheating and Plagiarism](#), “plagiarism includes, but is not limited to, failure to indicate the source with quotation marks or footnotes where appropriate if any of the following are reproduced in the work submitted by a student:

- A phrase, written or musical.
- A graphic element.
- A proof.
- Specific language.
- An idea derived from the work, published or unpublished, of another person.”

Any disciplinary actions regarding charges of cheating or plagiarism will follow the procedures

described in the “Carnegie Mellon University Undergraduate Academic Disciplinary Actions Overview” that can be found at <http://www.cmu.edu/policies/documents/AcadRegs.html>.

Collaboration vs. Cheating: Collaboration is defined by Merriam-Webster’s Collegiate Dictionary (10th edition) as “to work jointly with others or together, especially in an intellectual endeavor.” You are encouraged to discuss the course material, concepts, and assignments with other students in the class. **However, each student must eventually perform and submit his/her own unique work.** If any collaboration was used to complete an assignment, record the names of the collaborators and the nature of the collaboration. Any attempt to submit work that is not the student’s own work will be considered to be an act of cheating and will be subject to prosecution.

Expectations of Students and Instructors:

The instructors and teaching assistants have the right to expect the following of students:

1. Students will arrive to class on time and will be prepared for the lecture.
2. Students will turn in assignments on time (see policy on assignment due dates).
3. Students will follow the code of conduct regarding academic integrity, cheating, plagiarism, and collaboration as outlined in the syllabus.
4. Students will seek assistance when they need it.
5. If contacted by the instructor or teaching assistant by phone or e-mail, students will respond within 24 hours during the week and 48 hours on weekends.

The students have the right to expect the following of the instructor and teaching assistants:

1. A syllabus that describes class procedures, policies, and a course description will be provided (this thing you're enjoying reading, as we speak).
2. The instructors and teaching assistant will be available outside class during their posted office hours. The instructor or teaching assistant will also be available during other pre-arranged times if the student has course conflicts that do not allow them to attend regular office hours.
3. All assignments will be returned within two weeks after the due date.
4. E-mails to the instructor or teaching assistants from students will be returned within 24 hours during weekdays and 48 hours on weekends.