AC 2007-1990: CARDIOVASCULAR ENGINEERING: CURRENT STATUS, FUTURE TRENDS, AND ITS EMERGENCE AS A DISCIPLINE

Michael VanAuker, University of South Florida
Dr. VanAuker is presently an Assistant Professor in the Department of Chemical Engineering at the University of South Florida. His research focuses on cardiovascular engineering and targeted drug deliver.

Joel Strom, University of South Florida
Dr. Strom is a cardiologist who is presently a faculty member of the cardiovascular engineering group at the University of South Florida.

William Lee, University of South Florida
Dr. Lee is presently the Director of the University of South Florida Biomedical Engineering Program.

Cardiovascular Engineering: Current Status, Future Trends, and its Emergence as a Discipline

Abstract

Cardiovascular (CV) engineering is emerging as a defined discipline in engineering educational programs due to rapid advances in CV diagnostics, therapeutics, and rehabilitation. The growth in science and technology has in turn catalyzed significant industrial expansion as a wide variety of companies develop the high-tech products of the present and future. These advances require engineers capable of intimate interdisciplinary collaborations, particularly with CV physicians at each stage of research, but especially in the translational phase of product development. CV engineering education programs, whether defined as such or embedded in broader engineering educational programs include the following areas of study: underlying basic science issues involving CV anatomy and physiology, fluid characterization and flow, systems engineering, materials aspects of prosthetic devices, sensor devices, MEMS technology, drug delivery, imaging, etc. The purpose of this presentation is to define the current state of CV educational programs in engineering. All biomedical engineering programs identified by the Whitaker Foundation were reviewed to determine the extent of CV engineering education. The goals of this analysis are: 1) understand the extent to which "cardiovascular engineering" is indeed an emerging engineering discipline; 2) determine the extent to which academic programs in biomedical, mechanical, and other areas of engineering are starting to provide curriculum in this area (along with future trends); 3) determine the extent to which (like other established disciplines) a broader infrastructure exists (societies, journals, technical meetings, etc.); 4) provide information on the extent to which formal research groups focusing on cardiovascular engineering have been established; and 5) develop foundational arguments why cardiovascular engineering should indeed continue to become its own discipline. Information regarding the parallel growth in the industrial sector will be included in the analysis. Finally, the development of Cardiovascular Engineering at our own institution will be discussed.

Emergence of Cardiovascular Engineering as a Research Discipline

Biomedical Engineering is a rapidly evolving discipline. While many programs may have started as an affiliation of engineers from "traditional" disciplines building bridges with medical and biological realms, many now are emerging as entities quite distinct from other departments. Inspection of some standard textbooks reveals a broad overview of topics in bioengineering or biomedical engineering[1-3]. However, in contrast to the approach that a "biomedical engineer" should have a broad understanding of fields such as biology, anatomy, physiology, it is apparent that subspecialty areas have arisen in which the focus is on one particular organ, tissue, or system. Cardiovascular engineering is one such specialization.

Recently, journals have been created specifically for this field. In an editorial, Körfer identified the need to create a forum to bring together surgeons, cardiologists as well as other physicians, bioengineers, and "specialists from all medical, biological and technical disciplines", among others, who are interested in cardiovascular engineering problems, because he sees this as critical for the learning of new techniques and development of future innovations[4]. Likewise, a journal entitled "Cardiovascular Engineering: An International Journal" has been established to "promote innovative methods and technological advancements in the basic understanding of the cardiovascular system and in cardiovascular diagnosis and treatment applications"[5]. The authors of this paper (JAS,MDV) have also proposed a journal for this field. Of course, cardiovascular engineering would continue to provide significant contributions to the basic understanding of the cardiovascular system. This would include applications of fluid flow, rheology, modeling, and materials science.

Cardiovascular Engineering in the Private Sector

In a broad sense, the cardiovascular treatment-related market is huge. For example, the worldwide market was estimated to be worth about $60 billion in 1997 and was expected to grow to about $351.8 billion by 2003[6]. Much of the new growth will come from the Asia/Pacific region and the Latin-American region, which are expected to grow significantly by 2010[7]. In terms of all medical devices, the U.S. market was estimated to be approximately $86 billion by 2006 (close to $220 billion worldwide), with a projected 10% annual growth rate for the near future[8]. The U.S. medical device industry employs more than 411,400 individuals, about 1/3 of all biotech jobs[8]. Cardiovascular devices are a significant part of this market; Table 1 lists some of the dominant technologies. As one example of a specific product, the worldwide market for stents is estimated to be about $8 billion by 2008, with this growth reflecting advances in drug-eluting stents[9].

Dominant cardiovascular pharmaceutical companies include Pfizer, Bristol Myers Squibb, Novartis, GlaxoSmithKline, and AstraZeneca. For many pharmaceutical companies, cardiovascular-related therapies may account to 20-50% of their total market[10]. Espicom[11] lists 60 significant manufacturers of cardiovascular-related devices, including companies such as Abbott, Cordis, Boston Scientific, and Medtronic. In general, there has been an explosive growth of small biotech companies that are based on one or more cardiovascular device products.

Cardiovascular engineering product development normally focuses on the dominant incidence areas, including coronary artery disease, acute myocardial infarction, dysfunctional heart valves, transplantation technology, and peripheral vascular disease. Emerging areas of product development with strong engineering involvement include artificial heart components (from heart valves up to total artificial hearts), targeted drug delivery, diagnostic and monitoring approaches, artificial vessels (including stents) and technical advances in surgical techniques, including bypass surgery apparatus. From an engineering viewpoint, tissue engineering cardiovascular applications is expected to grow rapidly in the near future[12]. Tissue engineering includes organ regeneration technologies, artificial organs, biomaterials (natural and synthetic), cell transplantation, gene therapy, nerve regeneration, stem cells, tissue scaffolds, and related technologies.

Table 1
Cardiovascular devices involving significant engineering activity.

Pacemakers
Defibrillators
Stents, including drug-eluting stents
Catheters
Valves
Grafts
Artificial hearts
Artificial vessels
Angioplasty hardware
Guidewires
Ventricular support systems
Echocardiography
Targeted drug delivery devices
Perfusion systems

Analysis of Cardiovascular Engineering within Established Biomedical Engineering Programs

All biomedical engineering programs identified by the Whittaker Foundation (www.whittaker.org) curriculum database were reviewed to determine the extent of CV engineering education. Supplementary information was also obtained from the specific program's website. All programs were then entered into a database for analysis. Programs were subdivided into three groups: Group I: those a defined program, dedicated courses, and active research program in CV engineering CV engineering programs as identified on the Whit; Group II: those with embedded programs, those programs with demonstrated commitment to one or more major aspect of CV engineering education/research and have dedicated courses; and Group III: those lacking a CV engineering program.

One hundred and eighteen distinct biomedical engineering programs were identified; the University of North Carolina-North Carolina State University program was listed under both universities. Seventy-four of those programs were organized after 1990. Seventy-seven were organized as departments, 1 as an institute, 3 as schools/centers, and 29 as programs/divisions. Information was not available to determine the organization or no organization was reported in 8. Sixty-seven (87%) biomedical engineering departments were located in the College of Engineering, while only 18 departments/schools/programs were organized with intercollegiate governance, most often between colleges of medicine and engineering. Ninety-six programs award doctoral degrees.

Sixty-three of the 96 (66%) doctoral degree granting institutions have identifiable cardiovascular research programs. Table 2 lists the 21 institutions classified as Group I identified as having a specific program, dedicated courses, and active research program in CV engineering programs. The 24 institutions that have both dedicated courses and active research programs in CV engineering (Group II) are listed in Table 3. In addition, 18 other institutions classified in Group III have identifiable CV research programs, some extraordinarily productive.

This analysis confirms the rapid growth of biomedical engineering over the last 20 years. From a few dedicated departments and programs, there are now over100 most offering doctoral degrees. While cardiovascular engineering is not as clearly established and defined a neuro-engineering, it shares many of the characteristics. CV engineering is interdisciplinary whose applications involve all areas of biomedical engineering. As with neuro-engineering, there is intensive investigation in cellular, tissue, and organ regeneration and in the development of novel pharmacologic modalities and methods to deliver them. Both disciplines have very strong device development programs, and those developments have clearly impacted the care of patients and resulting outcomes.

This analysis has a number of obvious limitations. First, the information was derived from the Whitaker Foundation database, which has not been completely updated. Review of the institutional web sites was used to try to overcome inaccuracies due to obsolete data. However, given the rapidity at which biomedical engineering and CV engineering programs in particular are advancing, misclassifications and omissions are unavoidable without directly contacting each program, a feat that could not be accomplished in the time frame of delivering this manuscript

Table 2
Institutions Classified in Group I

Arizona State University
CUNY City College
Columbia University
Drexel University
Florida International University
Georgia Institute of Technology/Emory University
Johns Hopkins University
Harvard University/Massachusetts Institute of Technology
Northwestern University
Ohio State University
Purdue University
Stanford University
University of Alabama at Birmingham
University of California, San Diego
University of Miami
University of North Carolina/North Carolina State University
University of Oklahoma
University of Pennsylvania
University of Pittsburgh
University of Virginia
Washington University

Table 3
Institutions Classified in Group II

SUNY Binghamton University
California Institute of Technology
Case Western Reserve University
California Institute of Technology
Duke University
Louisiana Tech University
Marquette University
Mayo College of Medicine
New Jersey School of Technology
Rice University
Rutgers University
SUNY Stonybrook University
Texas A&M University
University of Colorado, Boulder
University of Iowa
University of Minnesota
University of Rochester
University of Southern California
University of South Florida
University of Texas, Arlington/SW Medical Center
University of Texas, Austin
University of Washington
Virginia Commonwealth University
Wright State University

Cardiovascular Engineering at the University of South Florida

Here at our institution, Cardiovascular Engineering has emerged as one of four main thrust for the Biomedical Engineering Program based primarily on pre-existing expertise and research interests among the faculty (the other three areas are Medical Imaging, Rehabilitation Engineering, and Biomechanics and Biomaterials). As a possible intermediate step toward a full fledged degree program specific to Cardiovascular Engineering, we have created a graduate certificate program that defines a focused set of courses. We seek to emphasize an engineering systems approach to understanding disease processes and developing new therapies and technology, but also to equip the engineer with basic vocabulary and skill sets in the disciplines of biochemistry and molecular biology. Therefore, the required 5-course sequence consists of two courses designed to apply engineering principles and analysis to the cardiovascular system. The remainder of the courses is chosen from courses in molecular biology and computational tools. Table 4 lists these courses, along with brief descriptions.

Table 4
Cardiovascular Engineering Course Sequence.

1. Cardiovascular Systems for Engineers **2. Biomedical Fluids and Cardiovascular Engineering** These two courses will form a sequence. In the first course, basic cardiovascular anatomy and physiology will be presented. Causes and consequences of disease will be discussed, and current therapy and diagnostic strategy will be discussed. The intent of the course is to equip engineers to "speak the language" of physicians and gain insight into clinically relevant questions that may be addressed by application of engineering principles to the design and analysis of biomedical problems. In the second course, the complexities of physiologic flow fields will be investigated, with special focus on the role of fluid mechanics in the development, diagnosis, and treatment of disease. Topics will include: models of cardiac mechanics and heart valve motion; wave propagation in the arterial system; flow in the microcirculation; invasive and non-invasive flow, velocity, and pressure measurements; the relevance of fluid mechanics to heart disease, atherosclerosis, and hypertension; and design issues for devices such as extracorporeal circuits, prosthetic valves, and cardiac assist devices.
3. Biochemistry, Molecular and Cellular Biology The overall goals of this course are to provide students with a solid foundation of biological and chemical principles that underlie cellular and pathophysiological processes and with a fundamental understanding of structures and processes of living systems at the molecular and cellular levels. The student will learn properties and functions of major classes of biomolecules, enzyme catalysis and regulation of metabolic reaction, the relationship between cellular structure and function, gene expression and how regulation is regulated, and responses of cells and tissues to normal and abnormal stimuli and the molecular basis for major disease states.
4. Biomedical Engineering Seminar Series
The final course is a computational course, currently either:
5. Bioinformatics An introduction to computer software applications for research in Biochemistry and Molecular Biology. Emphasis on database searching and submission, data analysis and graphical presentation, DNA and protein sequence analysis and molecular modeling.
Or
5. Finite Element Analysis This course introduces the finite Element method for structural analysis. Weighted residual and variational methods. Analysis of frame, plane stress/strain, axisymmetric, torsion, plate bending, shell and 3-dimensional elastic problems. Analysis of heat conduction, fluid flow, and electric and magnetic potential problems.

The authors (JAS, MDV) are currently working on a textbook that would be germane to the first two courses of this sequence.

Conclusion

In summary, CV engineering is an established discipline of biomedical engineering. This fact must be considered by institutions when planning for educational efforts, e.g. course and program development, research thrusts. The information presented here should be useful to engineering departments who are already participating in the area or who plan such an expansion.

Bibliography

1. Ritter AB, Reisman S, Michiak BB. Biomedical Engineering Principles. CRC Press, Boca Raton, FL, 2005.
2. Domach MM. Introduction to Biomedical Engineering. Pearson Prentice Hall, Upper Saddle River, NJ, 2004.
3. Enderle J, Blanchard S, Bronzino J. Introduction to Biomedical Engineering, 2nd edition. Elsevier Inc, Burlington MA, 2005.
4. Körfer R. Editorial In: Cardiovascular Engineering (Journal for Extracorporeal Circulation, Assist Devices, Transplantation and Artificial Organs). As cited by: http://www.pabst-publishers.de/Medizin/med%20Zeitschriften/cve/editorial.html
5. Cited by: http://www.ovid.com/site/catalog/Journal/1464.pdf
6. LeadDiscovery Ltd. The cardiovascular report. October, 2004.
7. Business Insights. The cardiovascular market outlook to 2010 (strategic report). January, 2006.
8. PharmaMedDevice, 2006. As cited by: http://www.pharmameddevice.com/App/homepage.cfm?appname=100485&linkid=23294&moduleid=3162
9. Assembly Magazine. Medical device frontiers: demand for cardiovascular products to remain high. December 8, 2004.
10. Cutting Edge Information. Cardiovascular marketing: budgets, staffing, and strategy (strategic report). March, 2004.
11. Espicon Business Intelligence. Who's developing what in cardiovascular devices? November, 2006.
12. Medtech Insight, Tissue engineering and cell transplantation: Technologies, opportunities, and evolving markets (report # A401). July, 2004.