AC 2007-2786: VANTH* BIOMEDICAL ENGINEERING KEY CONTENT SURVEY, PART TWO

David Gatchell, Northwestern University

David W. Gatchell is a research associate in the VaNTH Engineering Research Center for Bioengineering Educational Technologies and in the department of biomedical engineering at Northwestern University.

Robert Linsenmeier, Northwestern University

Robert A. Linsenmeier has a joint appointment in Biomedical Engineering in the Robert R. McCormick School of Engineering and Applied Science, and in Neurobiology and Physiology in the Weinberg College of Arts and Sciences. His primary teaching is in human and animal physiology. He is the Associate Director of the VaNTH Engineering Research Center in Bioengineering Educational Technologies, former chair of the Biomedical Engineering Department at Northwestern, and a fellow of the American Institute of Medical and Biological Engineering and the Biomedical Engineering Society. His research interests are in the role of retinal oxygen transport and metabolism in both normal physiological conditions and disease, and in bioengineering and physiology education.

VaNTH Biomedical Engineering Key Content Survey, Part Two. The 2nd Step in a Delphi Study to determine the core undergraduate BME curriculum

Introduction

A primary area of research for the VaNTH Engineering Research Center for Bioengineering Educational Technologies[1] has been to identify the concepts that should comprise a core undergraduate biomedical engineering curriculum. The motivation for this project has been described elsewhere[2-6] but, briefly, VaNTH domain experts believe that determining a core set of concepts will clarify for industry the capabilities of undergraduate biomedical engineers. In addition, these concepts should guide the development of new undergraduate programs in biomedical engineering and assist established programs in reworking their respective curricula.

The principal tool for determining the key concepts that comprise an ideal core curriculum has been the VaNTH Key Content Delphi Study. This study, conducted as a series of online surveys, has completed nearly two rounds, involving over 180 academic and industrial participants from the biomedical engineering community. The first round of the study was launched in 2004 and the second round was launched in 2006. Whereas results of the first round have been presented at several engineering and educational conferences, this is the first presentation of the results from the second round.

The purpose of this paper will be to summarize the key findings of the first two rounds of this study and to outline how these findings can be used to improve undergraduate BME education.

Methods

The Delphi method

The Delphi method (often referred to as a "Delphi study" in practice) was designed by the RAND Corporation in 1963[7] for forecasting technological and sociological change based on the collective opinions of experts in those respective fields. Recently, this method has been applied to a diversity of topics in science and engineering education including establishing biotechnology competencies for K-12 students[8], developing concept inventories in statics[9] and thermodynamics[10], and identifying core laboratory skills in the biomedical sciences[11]. The strength of this approach is that it capitalizes on the merits of group problem solving while minimizing its limitations, for example, group conformity inherent to round-table discussions[12].

Typically, a Delphi Study is comprised of several steps (see Clayton, 1997 for a lucid overview of this technique). In the first step, a group of experts is assembled and asked to brainstorm ideas relevant to a specified issue, e.g., forecasting important changes in the IT industry within the next ten years. In the second step, these ideas are collected and returned to the participants who are then asked to rate the relevance/importance of the ideas to the topic of interest. These responses are again collected and returned to the group. Individuals are asked to rate these concepts again, this time taking into account the responses from the previous iteration. In addition, participants are asked to support their responses, particularly if they are much higher or lower than the ratings determined in the previous step. This sequence of collecting, disseminating, and rating is continued until a consensus is reached regarding the importance/relevance of a set of ideas to the topic of interest.

Overview of the VaNTH Key Content Survey

The VaNTH Key Content Survey is a Delphi study focused on identifying key concepts that all undergraduate biomedical engineers should know upon graduation. The study is designed to undergo three iterations: 1) rate the importance/relevance of a comprehensive list of biomedical engineering, biology, and physiology concepts, as well as a list of co- and pre-requisite courses, to a core undergraduate BME curriculum; 2) revisit concepts from the first round which did not receive consensus ratings and introduce concepts recommended by participants in the first round of the survey; 3) rate the importance/relevance of sub-topics comprising the concepts rated as highly important/relevant in the first two rounds.

First Round

The first round of the survey, launched and completed in 2004, consisted of 274 concepts describing key topics in seventeen engineering, biology, and physiology domains. This set of concepts was extracted from taxonomies developed by VaNTH experts in the various BME domains. For all queried domains participants were asked to use a five-point Likert scale to assess their levels of expertise and were asked to rate the importance/relevance of concepts within these domains to an undergraduate core curriculum that should ideally be required of all BME students. In addition, participants were asked to suggest important concepts that had been omitted from the initial survey. We also questioned whether several co- and prerequisite courses in the basic sciences and mathematics should be required of all undergraduate BMEs (see Figure 1). Seventy-seven experts from academia, representing 33 universities, and 47 experts from industry, representing 17 companies, participated in the first round of this survey. First round data, and an analysis of this data, is posted at: http://www.vanth.org/curriculum/. Of particular interest are the concepts which were rated significantly different by academia and industry, for example, in engineering design.

Second Round

As stated above, all concepts in the first round of this study were scored using a five-point Likert scale (1 – very low importance/relevance to a core undergraduate curriculum, 5 – very high importance/relevance to a core undergraduate curriculum). From these ratings we calculated the median values (Q_2) and interquartile ranges ($Q_3 - Q_1$). The use of simple non-parametric statistics has been justified in the analysis of ordinal data[13] and has been used in other Delphi studies[10]. The parameters shown in Table 1 were used to determine whether a concept should be recommended for inclusion in an undergraduate core curriculum, not recommended for a core curriculum, or revisited in further iterations of the study. For example, in order for a concept to be recommended for the undergraduate core curriculum without revisiting it in the second round of the survey, the median (Q_2) must have been ≥ 4, the lower quartile ≥ 3, and the upper quartile ≥ 4. Of the 274 concepts queried in the first round, 166 met these criteria.

Non-parametric Measure			Action
Lower Quartile(Q_1)	Median (Q_2)	Upper Quartile(Q_3)	
$3 \leq Q_1$	$4 \leq Q_2$	$4 \leq Q_3$	Recommend
$Q_1 \leq 3$	$Q_2 \leq 3$	$Q_3 \leq 3$	Don't Recommend
$Q_1 \leq 3$	$1 \leq Q_2$	$4 \leq Q_3$	Revisit

Table 1: Statistical selection of key concepts

105 of the remaining concepts met the criteria in the last row of Table 1, thereby requiring that they be revisited in the second round of the survey. Of these 105 concepts, 59 were from engineering domains (as shown in Table 2) and 46 from the biology domains (e.g., physiology, cell biology, molecular biology, and biochemistry). To reduce the length of the second round of the survey, however, we only included the 59 engineering concepts. For the revisited concepts, as is common in a Delphi Study, we provided participants with the median ratings and interquartile ranges calculated from the first round data. Participants were asked to justify their ratings if they fell outside of the inter-quartile range for that concept.

The three remaining concepts:

- Artificial Intelligence (e.g., artificial neural networks, fuzzy logic, etc.)
- Statistical Physics (e.g., Bose-Einstein statistics; Fermi-Dirac statistics)
- Hormone Evolution

were all omitted from our list of recommended concepts. This is not surprising, however, as all three concepts were originally included in the first round to be "ringers", i.e., concepts that acted as reliability checks and were expected to be rated very low.

Thirty-one additional concepts from the original domains were suggested by participants in the first round and were integrated into the second round of the study as well. The distribution of these concepts across engineering domains is also shown in Table 2. In addition, 30 concepts from the biotechnology domain were included (this domain was not explicitly covered in the first round of the study).

Three additional questions completed the second round survey (see Tables 5, 6, and 7 below): 1) How should the undergraduate BME curriculum be structured? 2) Should a professional certification in BME be developed? 3) Will a core undergraduate BME curriculum improve industrial opportunities for undergraduate BMEs?

Domain	Revisited Concepts	New Concepts
General Engineering	2	3
Biosignals and Systems Analysis	6	1
Bio-Optics & Photonics	5	5
Biomechanics	1	1
Fluid Mechanics	1	4
Biomaterials	2	1

Bioinformatics	9	1
Engineering Design	13	3
Bioinstrumentation	3	2
Medical Imaging	2	2
Biothermodynamics	8	---
Heat and Mass Transfer	4	---
Engineering Mathematics	3	1
Cellular Biology	---	4
Physiology	---	3
Biotechnology	---	30
Co- and Prerequisite Courses	4	---
Total Concepts	63	61

Table 2: Distribution of concepts comprising the second round of the study

The second round of the VaNTH Key Content Survey was launched in the fall of 2006, and as of March 6th, 2007 it remained open for additional participation. At that point, 99 biomedical engineers had completed the survey, representing 50 universities and 36 companies.

Results

First Round

We applied parametric measures to the first round data in order to calculate the mean ratings for all concepts (a comprehensive list of this data is available at: www.vanth.org/curriculum/). These values allowed us to easily sort the data in order to determine concepts that were rated high by both academia and industry. Table 3 shows brief descriptions of the ten concepts rated highest by industry and the ten concepts rated highest by academia. X_I is the mean industrial rating of each concept and X_A is the mean academic rating of each concept. Full descriptions of thee concepts are available online.

Industry		**Academia**	
Concept	$\mathbf{X_I}$	Concept	$\mathbf{X_A}$
Descriptive Statistics	4.76	***Hypothesis Testing***	4.68
Measurement Concepts	4.71	***Principles of Statics***	4.68
Hypothesis Testing	4.65	***Descriptive Statistics***	4.62
Probability Distributions	4.62	DC and AC circuit analyses	4.55
Strength of Materials	4.57	Circuit Elements	4.55
Fundamental Properties of Polymers, Metals and Ceramics	4.50	***Mathematical Descriptions of Physical Systems***	4.53
Product Specification	4.45	Forces and pressures in fluids	4.53
Principles of Statics	4.43	***Strength of Materials***	4.51
Mechanical Properties of Biological Tissues	4.43	***Measurement Concepts***	4.51
Mathematical Descriptions of	4.43	Pressure-Flow Relations in Tubes and	4.50

Physical Systems		Networks	

Table 3: Ten first round concepts rated highest by Industry and Academia.

A comparison of the concepts in Table 3 shows that academia and industry have six concepts in common (shown in bold italics). Four of these concepts are from the Engineering Mathematics domain, three of which are topics in statistics. In contrast, Industry has two concepts from Biomaterials and one from Engineering Design in its top ten whereas Academia has two concepts from Fluid Mechanics and two concepts from Circuits in its top ten. An expanded list of the top 25 concepts rated by each group would show that 11 engineering domains are represented. This supports the idea that academia and industry desire breadth in an undergraduate biomedical engineering curriculum.

Second Round

One goal of a Delphi Study is to use the information gained in earlier iterations to inform the participants of the community's opinion of the concept. In the second round this was accomplished by providing the median ratings of the concepts in the first round as well as the interquartile ranges (25^{th} – 75^{th} percentiles). Comparing the ratings of concepts from the first round which were revisited in the second round provided some interesting results. In each of the 15 domains that we revisited, at least two concepts were rated significantly lower or higher than in the first round allowing us to either add them or remove them from our list of recommended concepts. In total, ratings for 23 concepts improved significantly and ratings for 14 concepts decreased significantly. Of the 31 new concepts suggested by participants in the first round, 7 met our criteria for recommendation (see Table 1) whereas 3 did not, i.e., they were rated low enough to warrant omission from our list of recommended concepts. Below, in Table 4, are some examples of concepts that received consensus ratings after being queried in the second round of the survey. Ratings of all second round concepts are available at www.vanth.org/curriculum/.

Domain	Concept	Recommend/ Not Recommend
Biosignals	Root Locus Plots	Not Recommended
Biosignals	Frequency Response Techniques (e.g., Bode plots, Nyquist criterion, contour mapping)	Recommended
Biosignals	***Properties of Digital Signal Processing; Analog to Digital Signal Conversion***	Recommended
Eng Mathematics	Chaos, Dynamical Instability, Non-Linear Mathematics	Not Recommended
Eng Mathematics	***Hypothesis Testing - Power Analysis (e.g., determination of sample size; reducing the probability of a Type II error, i.e., accepting a false hypothesis)***	Recommended
Bio-Optics & Photonics	Fourier Optics (e.g., temporal frequency; spatial frequency; Fresnel and Fraunhofer Diffraction; Fourier Analysis in 2-D; optical signal processing; holography)	Not Recommended
Bio-Optics &	Laser Cutting of Tissue (e.g., thermal ablation, UV	Not Recommended

Photonics	laser ablation, plasma ablation, photodisruption)	

Table 4: Examples of concepts from the second round meeting criteria for inclusion or exclusion from the recommended core curriculum (see Table 1). Concepts suggested by first round participants have been highlighted in bold italics.

Prerequisite Courses

Participants in the first round were asked whether the courses shown in Figure 1 should be required of all undergraduate biomedical engineers.

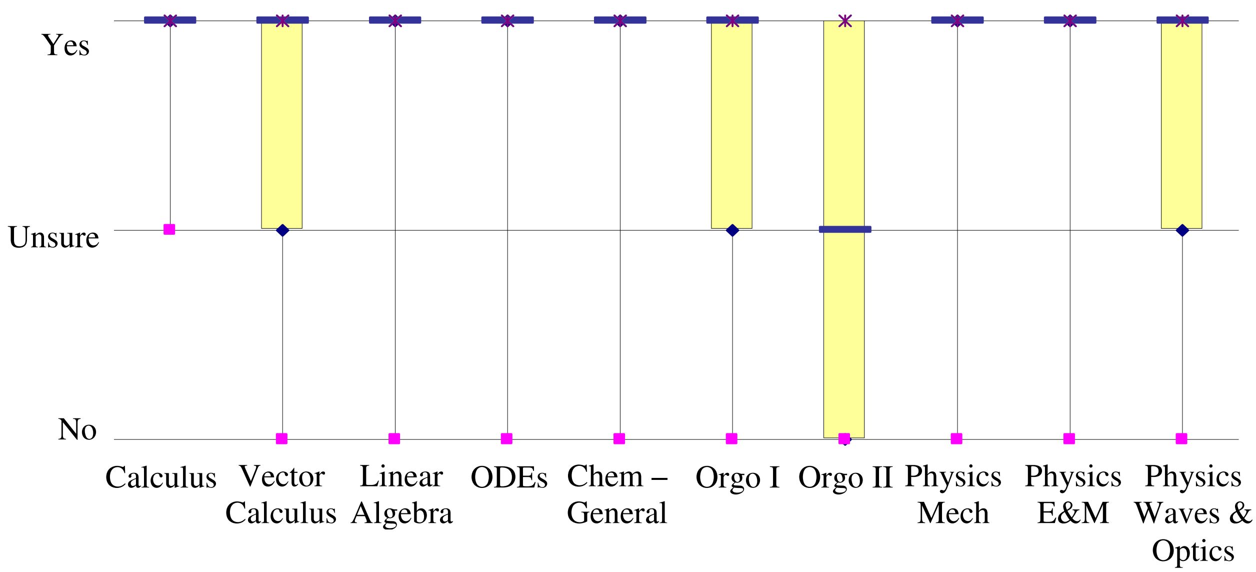

Figure 1: Box-and-whisker plot of first round responses to the question, “Should the following courses be required of all undergraduate biomedical engineering majors?” For each course the vertical boxes show the interquartile range and horizontal bars show the median response. If no box is present, the 25th percentile, median, and 75th percentile all have the same value. The (*) denotes the highest response and the (■) denotes the lowest response for each course. The courses, Vector Calculus, Organic Chemistry I, Organic Chemistry II, and Physics – Waves & Optics were revisited in the second round of the study.

From this figure it is apparent that experts recommend that six of the ten queried courses should be included in the biomedical engineering curriculum. Figure 2 shows the results of revisiting the other four courses in the second round of the survey, e.g., Vector Calculus, Organic Chemistry I, Organic Chemistry II, and Physics – Waves & Optics. Based on these results, there is strong agreement that Vector Calculus and Waves & Optics should be integrated into the core curriculum, first-semester Organic Chemistry should receive consideration, and second-semester Organic Chemistry should be optional.

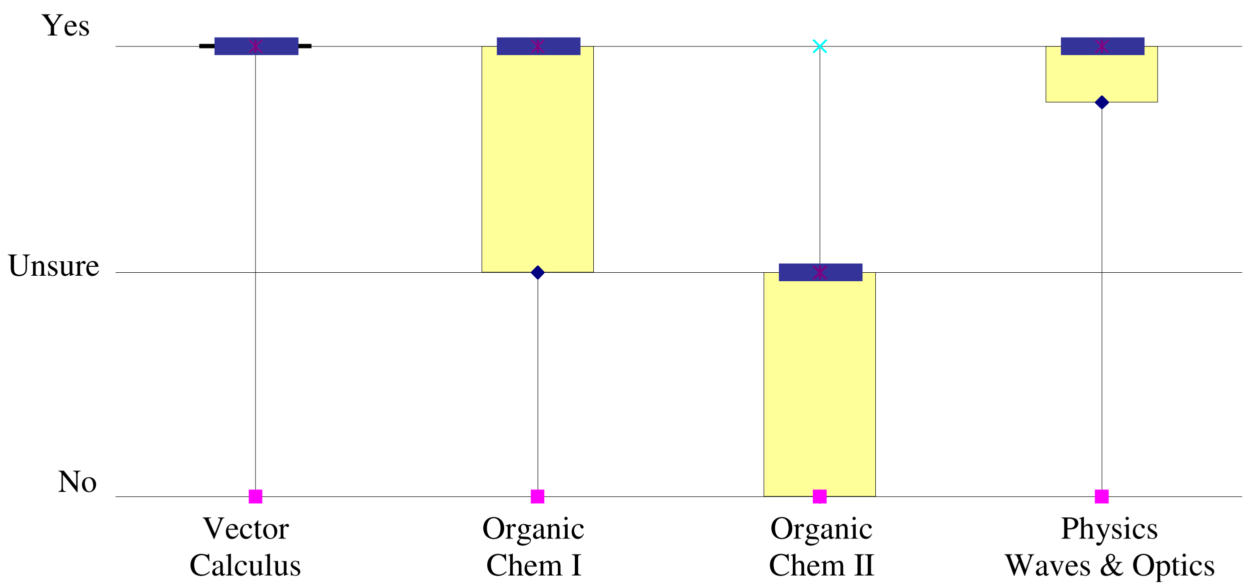

Figure 2: Box-and-whisker plot of second round responses to the question, "Should the following courses be required of all undergraduate biomedical engineering majors?" For each course the vertical boxes show the interquartile range and horizontal bars show the median response. If no box is present, the 25^{th} percentile, median, and 75^{th} percentile all have the same value. The (*) denotes the highest response and the (■) denotes the lowest response for each course.

In addition to the data summarized in Figure 2, participants were asked to support their responses to the question of whether these four courses should be required of all undergraduate biomedical engineers. In analyzing these responses we observed a division depending upon the BME concentration emphasized by the participant.

Vector calculus received 32 responses, 28 that were strongly for its inclusion (16 from academia, 12 from industry), and 4 that were against requiring vector calculus for all undergraduates (1 from academia, 3 from industry). In supporting the positive responses, some participants stated that knowledge of vector calculus is fundamental to engineering as a discipline, and others stated that many areas of bioengineering, e.g., mechanics, transport phenomena, and signal analysis, cannot be quantitatively understood without knowledge of its concepts. Three of the four negative responses were from industrial participants who cited little opportunity to apply these concepts in their current positions.

First-semester organic chemistry received 38 responses, 19 supporting its inclusion (11 from academia, 8 from industry), 12 against its inclusion (7 from academia, 5 from industry), and 7 which were uncertain as to whether this course should be included in a required core BME undergraduate curriculum (5 from academia, 2 from industry). Most of the comments related to positive responses stated that knowledge of organic chemistry is necessary for developing a fundamental understanding of biology and physiology. Those who were uncertain about requiring first-semester organic chemistry stated that this course can be difficult to fit into the curriculum and that an undergraduate understanding of biology, physiology, and biochemistry does not require knowledge of organic chemistry. One industrial participant stated that "organic chemistry is necessary for bioengineers but not classical engineers designing products that interface with humans." Of those against requiring first-semester organic chemistry many stated that the concepts comprising this topic are not uniformly applicable to all domains comprising biomedical engineering. One participant from industry bluntly stated, "Took it, have NEVER used it."

Second-semester organic chemistry received 26 responses, 4 supporting its inclusion (3 from academia, 1 from industry), 15 against its inclusion (7 from academia, 8 from industry), and 7 responses which were uncertain as to whether this course should be required of all undergraduate biomedical engineers (4 from academia, 3 from industry). Participants supporting its inclusion stated that an understanding of cellular functions requires knowledge of two semesters of organic chemistry. One participant recommended that a second semester of organic chemistry should de-emphasize synthesis reactions and focus on applications relevant to the field of biomedical engineering. Those who were uncertain of or against its inclusion stated that second-semester organic chemistry focuses too much on memorization and that its concepts are not well integrated into the biomedical engineering curriculum. Others commented that space in the curriculum is limited and that students are better off taking additional engineering courses.

Waves and Optics received 31 responses, 22 supporting its inclusion (13 from academia, 9 from industry), 6 against its inclusion (2 from academia, 4 from industry), and 3 responses (all from academia) which were uncertain as to whether waves and optics should be required of all undergraduate biomedical engineers. Of those supporting its inclusion, participants stated that knowledge of waves and optics is fundamental to understanding many biomedical engineering domains including imaging, instrumentation, and analysis of signals. Of those against including waves and optics in a core curriculum, participants stated that this course is only important for students interested in optics and imaging. One industrial participant argued that the concepts comprising a course in waves and quanta are not applicable to all positions in industry. The three participants who were uncertain as to whether waves and optics should be required stated that typical courses in this area do not focus on biomedical applications and, therefore, students requiring knowledge of these concepts can learn them within the context of their engineering courses.

Questions beyond the core curriculum

As mentioned above, the second round of the Delphi study included three qualitative questions. The first question asked of participants was, "Beyond the 'core content' that all undergraduate BMEs should receive, which of the following philosophies should be used in structuring the undergraduate BME curriculum?" Responses to this question are summarized in Table 5.

Option	Participants choosing option
Students should be required to follow a BME track clearly emphasizing depth in a traditional engineering field (e.g., a BME track in electrical engineering would require additional courses in circuit design, signal analysis, DSP, etc.)	28 (30%)
Students should be required to follow a BME track emphasizing depth in a traditional engineering field (as in option a.) or in an emerging area (e.g., cellular engineering, systems biology, tissue engineering, etc.).	32 (35%)
Students should take several courses in advanced bioengineering, guided by recommended sequences, but with flexibility of choice and not formalized as tracks.	19 (21%)
Students should be free to choose advanced courses from bioengineering, other branches of engineering, and biology based upon their own interests.	13 (14%)

Table 5: Options for structuring the undergraduate biomedical engineering curriculum

Of the participants responding to this question, 86% (n = 79) recommended that additional courses beyond the core curriculum be organized or structured in some way, e.g., tracks, concentrations, recommended course sequences. Fourteen percent (n = 13) recommended that students be given the flexibility to select their own advanced courses.

The second qualitative question was, "How much do you agree with this statement, 'The bioengineering community should work toward the creation of a professional certification and encourage students entering industry to obtain this certification.'" Participants were given a five-point Likert scale to share their opinions with a "No Opinion" option. Results are shown in Table 6 below.

Not at all	Very Little	Somewhat	Very Much	Completely	No Opinion
15 15%	27 28%	23 24%	16 16%	11 11%	5 5%

Table 6: Should the bioengineering community work toward the creation of a professional certification and encourage students entering industry to obtain this certification?

Participants were provided with the opportunity to explain their responses to this question. Most of the respondents were skeptical or against the development of a professional certification. Reasons given included:

- The field of biomedical engineering is too broad and diverse to be covered with a single certification.
- A professional certification would limit innovation within the field.
- The BME field is too new.
- Professional certification has become out-dated and we should focus instead on the development of our undergraduate programs.
- Who would determine what was on the exam?
- Professional licensure is often not desired by industry.

Other respondents were less skeptical stating that as the BME field matures this will become a "hot topic."

The third and perhaps most important question with regards to this study was: "To what extent do you agree with this statement, 'Employment opportunities in industry for bioengineers would improve if academia adopts a core BME curriculum.'" Participants were again given a five-point Likert scale to share their opinions with a "No Opinion" option. Results are shown in Table 7 below:

Not at all	Very Little	Somewhat	Very Much	Completely	No Opinion
6 6%	27 28%	40 41%	16 16%	7 7%	1 1%

Table 7: To what extent do you agree that employment opportunities in industry for bioengineers would improve if academia adopts a core BME curriculum?

Again, participants were provided with the opportunity to explain their responses to this question. Of the 25 submitted responses, 12 were supportive of the development of a core curriculum, 3 were neutral, and ten were against it. The primary criticism was that the field of biomedical engineering is too broad and a core curriculum would only consist of courses in the basic sciences and mathematics. Supporters stated that developing a core curriculum would help to clarify for industry what skills and knowledge biomedical engineers possess. Others stated that a core curriculum may be beneficial but only if it is developed and promoted by the community as a whole.

Discussion

The primary goal of the VaNTH Key Content Survey has been to determine the key concepts that should comprise an ideal core undergraduate curriculum in biomedical engineering. In 2004 we launched the first round of the survey and have followed this up with the launching of a second survey in 2006. As of March, 2007, the VaNTH Key Content Survey had solicited feedback from over 180 academic and industrial biomedical engineers. For the second round alone, we have received 99 responses, 59 from academia and 40 from industry. Though the survey remains open to additional participation, certain themes are clear and the conclusions of this paper should not change significantly once the survey has been closed. First, there is strong agreement between industry and academia on which topics are important, with significant divergence occurring on only a handful of concepts (see www.vanth.org/curriculum/). Second, no engineering domain dominates the list of concepts that all biomedical engineers should know, and the striking characteristic expected of biomedical engineers is breadth. Our analysis of biomedical engineering programs[14] shows that this breadth is already being incorporated. Third, about 65% of our respondents feel that working toward a core is valuable for improving employment opportunities of biomedical engineers, and that ~85% feel that beyond the core some type of specialization is required at the undergraduate level.

One of the major concerns of this study has been how to use these results as a tool to assist undergraduate programs in developing new curricula and reworking existing curricula. New undergraduate BME programs at Ohio State University, Carnegie Mellon, and Florida Gulf Coast University have used the results from the first round in the development of their programs. Others, such as Stony Brook University, have used results from the first round to re-design their curricula, emphasizing concepts that industry has rated significantly higher than industry (see www.vanth.org/curriculum/). At Northwestern University, we have mapped the highly rated concepts onto our standing curriculum and used these results to require, rather than recommend, biomechanics and signals and systems, and to drop one quarter of organic chemistry. One vision of this study is that programs will identify concepts that are not comprehensively covered by their respective curricula and introduce courses and materials emphasizing these concepts. For example, our results show that opportunities for learning and applying statistical tools to real-world engineering problems cannot be overemphasized. Of the 25 concepts rated highest by industry, five were from the statistics section of the engineering mathematics domain. In addition, the concept “Hypothesis Testing – Power Analysis”, recommended by a participant in the first round, received an average rating of 4.19 by our industrial participants and an average rating of 4.22 overall.

In our analysis of the ratings of 274 concepts comprising the 17 engineering, biology, and physiology domains of the first round of this study, we found only three concepts that were rated low enough to warrant omission from our list of recommended concepts (see row four of Table 1). Omission from our list of recommended concepts, however, does not imply that the concept should not be included in the non-core curriculum, e.g., within biomedical engineering tracks or areas of specialization. For example, whereas it is highly unlikely that a career in designing biomaterials or biomedical devices would *require* knowledge of "Artificial Intelligence", a career in bioinformatics may require some familiarity with this concept. This knowledge can be gained from advanced courses in this discipline, and not from courses required of all undergraduates.

In the second round of this study we revisited concepts which did not receive consensus ratings in the first round, i.e., the ratings did not meet the criteria for inclusion in, or exclusion from, the recommended curriculum (see Table 1). Participants were asked to rate the importance of these concepts, this time taking into account the median ratings and inter-quartile ranges for these concepts from the first round. If a participant rated a concept outside of its first round interquartile range, they were asked to explain why. For the majority of the concepts queried this did not occur. As the field moves toward further recommendations about a core curriculum, it may be that such concepts, about which there is a considerable diversity of opinion, will be placed in the core curriculum at some universities, in areas of specialization by others, and omitted altogether at still others. There is no desire to have all biomedical engineering programs conform to a single, standardized curriculum, and this is one way of insuring that some variability is achieved. In this context, it is worth pointing out that the core is expected to leave considerable room for topics that have not been included in the survey, further allowing programs to distinguish themselves.

As described above, the VaNTH Key Content Survey was originally designed for three iterations. The third iteration would ask participants to rate sub-topics comprising the highest rated concepts queried in the first two rounds. Given that VaNTH is in its eighth and final year of funding, the timing of this last round is uncertain. At present, we are expecting to launch the third round of the survey by August of 2007. An additional round could also be added in which proficiency levels expected of undergraduate biomedical engineering students are determined with respect to the topics identified in the first three rounds[4].

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