Engineering in Clinical Practices: An Evidence-Based Review of Two-Course Sequence

Charlotte Da Jung Sevrain, Vanderbilt University

Charlotte Sevrain is a junior at Vanderbilt University, pursuing a degree in Biomechanical Engineering. She serves as an undergraduate research intern with the Vanderbilt Institute for Surgery and Engineering (VISE), where she has contributed to innovative research for a year.

Nathan Zhang, Vanderbilt University

Nathan Zhang is a undergraduate studying biomedical engineering at Vanderbilt University working on biomedical engineering education in conjunction with the Vanderbilt Institute for Surgery and Engineering.

Dr. Michael I. Miga, Vanderbilt University

Michael I. Miga, Ph.D. received his B.S. and M.S. from the University of Rhode Island in Mechanical Engineering and Applied Mechanics, respectively. He received his Ph.D. from Dartmouth College specializing in biomedical engineering. He joined the facul

Dr. Stacy S Klein-Gardner, Vanderbilt University

Dr. Stacy Klein-Gardner serves as an Adjunct Professor of Biomedical Engineering at Vanderbilt University. She is the Executive Director of Engineering For Us All (e4usa). She provides educational evaluation for the Vanderbilt Institute of Surgery and Engineering's NIH-funded T32 training grant. Dr. Klein-Gardner is a Fellow of ASEE and AIMBE.

Engineering in Clinical Practices:
An Evidence-Based Review of a Two-Course Sequence

Abstract:

The impact of two Biomedical Engineering (BME) graduate level courses, BME 6301: Engineering in Surgery and Intervention — Provocative Questions, and BME 6302: Engineering in Surgery and Intervention — Clinical Interactions, is explored in this study. Designed to integrate an engineering approach into clinical practices, these courses aim to bridge the gap between theoretical understanding and real-domain applications.

The first course in the sequence, BME 6301, is a structured clinical experience in the classroom that focuses on the intersection of engineering and surgery through the analysis of provocative questions, driving innovation in surgical techniques. The following course, BME 6302, is less structured and more immersive and delves into analyzing the workflow of surgery and intervention which assists class discussions on the translation of engineering research in clinical settings and the synthesis of novel provocative questions.

To assess the courses' efficacy, three researchers conducted a study involving recruiting 10 of 16 alumni of the courses to participate in a brief survey and interview. The interviews were transcribed and imported into a qualitative data analysis program. Using inductive coding analysis and a constant comparative method, codes were then generated by identifying patterns and themes within the interviews. The process yielded a total of 31 codes consisting of 11 main codes and 20 sub-codes through three rounds of coding review sessions. After all interview transcripts were coded, the frequency and coding types were analyzed.

Overall, the courses were found to be highly impactful. Many of the trainees generally reported a strong sense of engineering identity and self-efficacy for their work. Alumni reported benefits not only during graduate school but also immediately in their careers. During graduate school, they report that these courses pair well with more technical courses and that many students included their partner surgeon on their thesis committee. These benefits also include writing skills and shadowing experiences, giving them insights into the inner workings and workflow of the operating room. Trainees have carried these experiences forward into their jobs now.

Introduction:

This study explores the professional and career-related impact on students who completed a two-course sequence of Biomedical Engineering (BME) graduate level courses focused on clinical immersion, BME 6301: Engineering in Surgery and Intervention — Provocative Questions, and BME 6302: Engineering in Surgery and Intervention — Clinical Interactions.

Theoretical Background:

Immersion courses—specifically in the biomedical engineering field—provide a hands-on experience, delving into theoretical knowledge combined with real-world scenarios. These

courses often offer students the opportunity to shadow physicians, observe surgical procedures, engage in discussions, and participate in identifying healthcare needs and proposed solutions. The primary objective is to give students a deeper understanding of the clinical setting and workflow and to utilize engineering principles ultimately to address medical needs and problems in patient care through innovation.

In 2023, Guilford, Kotche, and Schmedlen published a survey of clinical experiences in biomedical engineering [1]. This study summarizes many of the outcomes and provides many descriptive statistics of these immersive programs.

> "Outcomes [of immersion in clinical environments] that have been reported include gains in critical-thinking and problem-solving skills; increases in in grade point average; the identification of unmet clinical needs; creation of prototypes, student-led design-based conference and journal publications, peer-to-peer mentoring of non-immersion participants; understanding of procedural medicine; an ability to pose important questions about things that affect human health; interpersonal communication with clinicians, and working with clinicians to identify unmet needs and influence on career path" [1].

This study on biomedical engineering immersion goes on to emphasize the importance of aligning courses with learning theories, goals, and assessments—clinical immersion programs should be "firmly grounded in appropriate learning theory to avoid misalignment between the stated objectives of clinical immersion programs and the assessments thereof" [1]. Constructive alignment establishes cohesive program objectives, assessments, and teaching techniques designed to maximize learning outcomes. This alignment is valuable in assessing the effectiveness and success of clinical immersion experiences in meeting the stated learning objectives. Additionally, the paper highlights the crucial role program density and structure (high- and low-density) has in shaping the impact on students' learning experiences. Graduate immersion courses and programs tend to have a lower density of immersion compared to undergraduate courses, though the program duration may be lengthier. Future areas of research noted include whether high- or low-density programs are more effective in achieving better outcomes of clinical immersion.

The immersion model being analyzed in our paper collectively falls in between the low- and high-density immersion experiences as reported in [1]. BME 6301 represents a low-density immersion course due to its structured, clinically-driven approach with limited clinical contact (70 minutes per week). BME 6302 represents a high-density immersion course due to its lengthier duration (200 minutes per week) of clinical contact and shadowing physicians in the OR. Equally noteworthy, while the discussion in [1] expresses the importance of structure, the nature of immersion experiences, and the alignment of reporting functions as being critical, their analysis was largely focused at the density metric. In contrast, our paper extends on [1] by evaluating courses through the assessment of learning approaches based on their career impacts.

Immersion Courses:

BME courses typically either heavily focus on theoretical principles or specific technical skills without deep clinical application, lacking immersive experiences like clinical interactions—between the student and physician—and surgical shadowing. [1]

The Guilford, Kotche, and Schmedlen paper examines 84 institutions where 62 reported having either a clinical immersion program or course. 67.5% of the clinical immersion experiences were directed at second- through fourth-year undergraduate students [1]. In these biomedical engineering immersion programs, graduate students tend to have fewer hours in clinical environments compared to undergraduate students, though more graduate students tend to participate in immersion experiences—overall, the graduate immersion experiences tend to be less "dense."

Carnegie Mellon [2] and Virginia Tech [3] both have a course focused on interacting with clinical practitioners to investigate problems faced in the OR. Carnegie Mellon's "Surgery for Engineers" course offers a hands-on experience, observing procedures that use surgical technologies. Virginia Tech's "Clinical Rotation" course offers a broad overview of engineering in medicine, where students also observe clinical operations. While both courses combine engineering principles with clinical applications, they lack: (1) an organized interaction of unstructured and structured learning activities, (2) the immersive analysis of surgical workflows, and (3) a problem-centric approach.

Johns Hopkins University (JHU) researchers [4] note that identification and validation are key elements of undergraduate engineering capstone design and that the process is enhanced by clinical observation and root-cause analysis. Limiting factors to implementing this for large groups of students include limited physician time and expense, small observation groups at any one time, and non-rigid scheduling of procedures. JHU implemented a team-leader training model, where students interview to represent their team in this capacity and take part in an intersession course focused on clinical observation and immersion. Self-reported surveys show that students had a positive immersive experience. Researchers noted the connections formed with their clinical mentors and a deeper understanding of medical needs.

Many other clinically-oriented biomedical engineering courses exist beyond the ones mentioned above. It is important to note that our study focuses on surgery within the field of engineering, though other institutions may emphasize different areas of immersion, such as imaging. These programs offer valuable clinical experience by providing engineering students the invaluable opportunity to improve their problem identification, and sometimes problem-solving skills. However, whether due to length or resources, many of these programs tend to lack integrated grant-writing and discussion-based components. Teaching grant-writing skills to graduate students proves to be useful later in their careers as it drives students to research in their fields extensively, emphasizes the role of innovation in research, and enhances the skills needed to display and discuss data [5]. The discussion-based format is vital in enhancing critical thinking and engagement, promoting collaborative problem-solving, and sharpening communication skills amongst peers [6]. Beyond just being able to identify and solve current clinical needs, developing adequate writing skills is crucial for graduate students' success. Our goal is to design a course that implements clinical immersion to develop students' problem identification, problem solving, and grant writing skills.

The Courses in This Study:

The two-course sequence assessed in this study aims to integrate an engineering approach into clinical practice, bridging the gap between theoretical knowledge and real-domain applications. The stated goal of the two courses is to prepare students with a comprehensive experience in applying biomedical engineering principles to novel problems identified through discovery discussions with physicians and direct observations within the clinical environment. The two-course sequence imparts a critical development skill for biomedical engineering students pursuing hypothesis-driven work within procedural medicine systems, namely, the ability for students to identify the most pressing problems in the delivery of procedural medicine that may or may not align with clinical perception, and then to actualize engineering solutions within clinical contexts. More specifically, a common limitation in the training of biomedical engineering students is the over reliance on clinical perception coming at the cost of engineering innovation. While clinical training is evolving, the Halstedian model [7], [8] of 'see one, do one, teach one' is still the predominant training framework and is designed to perfect procedure and is not a recipe for innovation. The 'real domain experiences' dialogue introduced by Miga and Labadie [9] allows for a better balance between the explicit experience of the clinician and the innovative nature of the engineer. BME 6301 and BME 6302 are specifically designed to create that balance and go beyond theoretical training, driving innovation in surgical techniques and incorporating grant writing and budgeting into clinical immersion. Pedagogically, the immersion approach differs from other programs in that it is focused at an organized approach consisting of both constructionist and constructivist experiences, i.e., both structured and unstructured clinical immersion experiences [9]. Additionally, these courses are required for students whose funding comes from an NIH T32 training grant, and they are not required of all BME graduate students.

BME 6301 focuses on the intersection of engineering and clinical aspects through clinically-driven provocative questions that push advancements in surgical techniques. Provocative Questions (PQs) [9] are said to have the following characteristics: identifies a procedural barrier or missing area of knowledge that affects delivery of care, inspires analysis and design approaches that are focused at solutions with strong engineering needs, and if solved will have a significant clinical impact on health or our understanding of disease. In BME 6301, the students refine physician-presented PQs throughout the course, which are identified by those physicians invited to the class. These physician-presented provocative questions are provided over the course of a semester (14 weeks) through 13-15 different physician presentations, resulting in 70 minutes per week in direct clinical contact time. In BME 6302, the course focuses on having the students independently identify PQs based on observation and interactions with physicians, enhancing their problem-identifying and -solving skills.

BME 6302 delves into the direct observation of clinical technologies, surgical workflows, the application of surgical and interventional techniques, and attendance at clinical conferences to understand the trajectory of care. Students are assigned to a surgeon for the semester, giving students the opportunity to closely observe clinical practice, as well as identify provocative questions, and to analyze clinical workflows. It should also be noted that while students have one primary mentor, they often experience interactions with additional members of the clinical practice. Student-reported data indicated an average of 50 +/- 13.6 hours of clinical contact over

the 14-week semester and reflected a range of minimum semesterly contact time of 30 hours (~2.1 hours per week) to a maximum of 80.5 hours (~8 hours per week) over the entire cohort. All students also spent one additional hour per week (total of 14 hours) for in-class reflective activities on their experiences as well. In addition, weekly written assignments and in-class discussions allow students to collaborate and reflect on their experiences in the operating room (OR). The course also consists of three larger assignments through the semester: a review paper, a research needs assessment, and a culminating mock R21 grant proposal. In the first assignment, students are asked to generate a narrative synthesis in a systematic review paper that will create a sustained, powerful influence on the field at hand. In many respects, this review paper serves as one of the first substantive collaborations with a physician as this is done in very close collaboration with their clinical mentor. The needs assessment requires students to identify a gap in the current state of therapy in an area of their choosing. After identifying the barriers, characterizing them, and verifying them, the student proposes a solution. This needs assessment culminates in the writing of the specific aims section for an NIH proposal on a new project. This assignment serves a different goal with the student's clinical mentors taking on the role of key opinion leaders in the field. While this guidance is one source of data for the assignment, the students also make their own observations bringing their own expertise; and additionally, other influences from the scientific community are also consulted. The course is completed with the last assignment with students authoring a mock R21 grant proposal, including project summary, biosketch for the student, budget, specific aims, research strategy, and references. This serves as a culmination point for the program with the student really bringing together all components of their immersion into a high impact exploratory proposal. While it is not required, the students are afforded the opportunity to provide their clinical mentors with their proposal for feedback.

As an exemplar, one BME 6302 student's work is provided here. The student was a pre-doctoral mechanical engineering graduate student with a neurosurgeon clinical mentor specializing in endovascular neurosurgery. Within this student's BME 6302 course, they observed 31 procedures, 17 different types of procedures, one morbidity and mortality clinical conference, with a total clinical contact time of approximately 70.5 hours. Beginning with their observation, the student witnessed a procedure in which the patient needed to have cerebrospinal fluid drained from the ventricles to release pressure within the brain. As part of the drainage process, a cannula had to be tunneled under the skin down into the stomach. Observations revealed an extremely forceful process, a lack of control, a need to visualize anatomy, and a continuous concern that a complication of collateral organ penetration could take place. This led to a provocative question, *"Is it possible to improve this physically-demanding surgical effort so as to safely navigate and visualize the anatomy to reduce the risk of complications?"* These questions led to the student's mock R21 proposal with the stated hypothesis, "*Our hypothesis is that by reducing tissue penetration forces, enabling tunnel path modifications intraoperatively, and implementing image guidance with ultrasound, the rate of iatrogenic events during shunt tunneling will be reduced.*" The aims reflected a comprehensive consideration of tissue disruption methods, a novel steerable tunneling system, combined with ultrasound guidance approach. While the engineering methods of steerability were a focus of this student's training, the application, guidance approach, and the clinical significance were novel.

Goals:

This paper reports on qualitative research methods to assess the efficacy of a two-course clinical immersion sequence. Using the data collected from alumni individual interviews, this study aims to evaluate the impact of BME 6301 and BME 6302 on alumni who have completed the sequence. The subsequent sections detail the methods used in instrument creation, data analysis, subject recruitment, and provide an educational outcome of the courses. The research question is: "*What is the impact of the two BME courses on alumni careers, particularly the translation of clinical and engineering knowledge into professional development?"*

Participants:

BME 6301 is open to all graduate students in MS, MEng, PhD as well as other graduate programs in the School of Medicine, but BME 6302 is limited only to those who have successfully completed BME 6301, with most students funded through the T32 training grant funding this research. Students typically take these courses in the spring of their first year of graduate school and fall of their second year of graduate school, respectively. Some students are in the medical scientist, MD/PhD program. Since the courses' creation in 2016, a total of 29 trainees have taken the two-course sequence and 17 have graduated. At the time of the study, 16 alumni had graduated, and 10 agreed to be interviewed. Their general field and company location are specified in Table 1.

Table 1. Career Path and Company of the 10 Interviewed BME 6301 and BME 6302 Alumni

Career Path	**Company**
Industry	Siemens
Industry	X-Rite
Industry	PolarisAR
Industry	Hyperfine
Industry	Boston Scientific
Academia	Memorial Sloan Kettering Cancer Center
Academia	Ohio State University
Academia	Michigan Medicine
Start-up	EndoTheia
Start-up	VenoDynamics

Methods:

The interview questions were a set of mostly open-ended questions designed to understand the impact of the course. This work was approved by the Vanderbilt University Medical Center's IRB under protocol #210303. Original suggestions by the course instructor and program director were based on course expectations and further questions were brainstormed. To minimize potential bias and ensure that prior questions did not influence responses to later ones, a general interview protocol was followed that prioritized open-ended questions that allowed for natural flow in the conversations. Because many alumni did not end up pursuing a career in academia where grant writing would have been an intensive focus, an additional survey question

was included regarding budgeting. The final interview questions are displayed below in Table 2, with questions ordered as planned to be introduced, though each interview was a conversation and at times interviewees brought up topics in a different order.

Table 2. Final Version of Alumni Interview Questions

#	Question	Category
1	What made you choose the course(s)?	Current Career Path Impact of Two-course sequence
2	Since completing your degree can you tell us about your work experiences and a one sentence description of your responsibilities? • Organization • Position Title • Dates Employed	

3	With each experience above, has your clinical immersion at this institution had an impact?
	• Rate the value of your clinical immersion experience
	  o No impact
	  o Some impact
	  o Moderate impact
	  o High impact	

4	How do you think your engineering identity plays a role in your career today?	
5	Self-efficacy is defined as an individual's beliefs in their own capacities to perform a certain action. How do you think your engineering self-efficacy plays a role in your career today?	
6	As you look back, what were your biggest takeaways from the clinical immersion course(s) you took at this institution? • Was this course(s) more useful than other courses in graduate school? • Are the skills you learned in the course(s) still relevant today?	
7	Did you find yourself more prepared to write grants/submit NIH or other proposals?	Engineering and Professional Skills
8	What do you remember about provocative questions, what they are, and how we identify them?	
9	Based on Miga and Labadie [9], we define a Provocative Question (PQ) to have the following characteristics: • Identifies a procedural barrier and/or missing area of knowledge that affects delivery of care	

	• Inspires analysis and design approaches that are focused on solutions with strong engineering solutions • If solved will have a significant clinical impact on health Given your career experiences, would you redefine the concept of provocative questions from the understanding you gained in your course work? (Yes or No). • If so, how would you redefine provocative questions?	
10	Given your career experiences, would you redefine the concept of clinical interactions from the understanding you gained in your course work? (Yes or No) • If so, how would you redefine clinical interactions?	
11	In the second part of the course, you were asked to give a budget in your mock grant submission. Do you feel like that improved your ability to create a financially viable product in your work now?	
12	Where would you make improvements to the clinical immersion courses?	Course Reflections and Improvements
13	Do you think the design of the course worked?	
14	If you were to take the course now, what would you have done differently?	
15	What would you say to students currently taking the course?	

Prior to each interview, trainees were given a pre-interview survey where they were asked to fill out basic information regarding when they took the classes, their degree, and a brief description of their current work. All interviews were conducted online via zoom and the resulting interviews were recorded and transcribed using the online transcription tool Otter.ai [10].

After importing the interview transcripts into Dedoose [11], a qualitative data analysis program, codes were generated by identifying patterns and themes within the ten interview responses. The process involved three individuals coding separately and reconvening to discuss and refine codes through consensus among the research group. After three rounds of coding review, a total of 31 codes comprised of 11 main codes and 20 sub-codes were created to organize and interpret the data. After all interview transcripts were coded, frequency and types of codes were analyzed and compared.

Results:

Codes and their frequencies are indicated in Table 3's full generated Codebook. The "number of mentions" indicates the number of times the particular code appeared across all interview transcripts, while the "number of unique students discussing the code" refers to the number of the 10 total interviewees who mentioned that code. Several codes were particularly frequent and widely discussed—*Related to Funding* (mentioned 11 times by 7 students), *Interactions with Clinicians* (mentioned times 16 by 7 students), and *Seeing the Bigger Picture* (mentioned 23 times by 8 students). Other commonly referenced codes were *Experience with the Course*, *Alumni's Definition of Provocative Questions*, and *Exploring Outside the Field*.

Overall, the course was found to be impactful with 90% of the interviewed alumni reporting the course was moderate to high impact. One alumnus said, "There are aspects of it that I couldn't get in any other class, or any other course. So, there are parts of it that were more impactful or more useful to me."

Table 3. Generated Codebook

Main codes are shown in **bold** and sub codes in *italics*.

Main Code	Sub Code	Description	Number of mentions	Number of unique students discussing the code
Career Path		Trainee identifies and describes their career path after graduating from the T32 program	0	0
	Academia	Trainee is working in academia, typically for some educational or health institution	8	4
	Industry	Trainee is working in industry, typically in a setting where they are not the only engineer	5	4
	Startup	Trainee is working for a startup company, typically in a setting where they are the only engineer	5	3
Experience with the Course		Any shadowing experience that is specific to the trainee's experience. This generally involves specific events such as rounds, procedures, and/or surgeries	16	6

Grant Writing		Anything the trainee learned or experienced that improved their ability to write grants	8	6
	Related to Funding	Anything the trainee learned about when writing about budgeting and applying to funding	11	7
	Research Manuscript	Success in writing research manuscripts that require a clinical perspective	2	1
Impact of Clinical Immersion Course		Trainee describes the impact of the clinical immersion course	8	5
	Continued Value of OR Knowledge	Trainee's OR knowledge continues to be used in their current work setting	7	3
	Interactions with Clinicians	Trainee's insights and interactions gained from clinicians	16	7
	Networking and Connections	Trainee develops important networks/connections from the course	5	3
	Non-OR Clinical Experience	Trainee's clinical experience and understanding of the medical environment outside of the OR	6	6
	Seeing the Bigger Picture	Trainee understands or recognizes the larger problem	23	8
	Success in Being Hired	Trainee believes they were hired as a result of their experiences in these classes	3	3
	Time Management	Trainee's experience in the course has improved their time management	8	3
	Translational Research	Trainee recognizes the importance of bench to bedside research	9	6
	Workflow in the OR	Trainee obtains observation or insight regarding the workflow in the operating room	9	4
Limitations of Course		Anything mentioned that demonstrates the limitations of the 2 two semester clinical immersion course	3	2
Potential Improvements to Course		Trainee identifies potential areas that could make the course better	9	5
	Exploring Outside the Field	Trainee recommends exploration outside of their field of interest	13	8
Provocative Questions		Anything mentioned that relates to provocative questions	0	0

	Alumni's Definition of Provocative Questions	Trainee's definition of provocative questions based on how they remember and understand it	13	9
	Provocative Question Identification	Trainee actively identifies provocative questions in a clinical environment	5	3
Questions for the Interviewer		Trainee asks the interviewers a question	5	4
	Importance of Provocative Questions	Trainee recognizes the importance of provocative questions in their field	5	4
Trainee Background		Trainee mentions anything related to their background	4	4

Although most interviewed alumni are not working in academia, many of the trainees still found the writing skills and shadowing experiences to be useful for their current jobs at startups and industry. One alumnus stated, "It's been useful to have to have come into this [current job] position with, with surgical experience. And I think it's honestly one of the reasons they hired me." Even alumni who were not working in the same fields in which they shadowed believed that the courses were helpful as they gave them an opportunity to understand the inner workings and workflow of the operating room. Another alumnus said, "Understanding the clinical process and being able to be in operating rooms and see firsthand what clinicians experience and the problems they face is pretty central to my job now, because [it is] part of making a product that physicians will eventually use." Additionally, the course was said to pair well with other technical-focused graduate courses by offering a new angle. One alumnus said, "Some of the core technical courses that we did about medical image analysis or AI, those are equally important as well. You need to have both strong technical skills, as well as translational thinking."

During the course, each student is assigned a physician to shadow in the OR. Feedback for potential improvements in the second course highlighted the need for opportunities to explore beyond their assigned surgeon's domain and more time dedicated to debriefing with physicians. One alumnus reported that, "I stuck with the same surgeon for almost the entire class, which logistically is probably like the best way to do it. But if I were doing it again, I would try to branch out and see some surgeries that were a little bit more outside of the domain I was staying in. Because I really learned over time, especially with clinicians that everybody has kind of their own way of doing things and seeing different perspectives and different ways of approaching similar problems is pretty valuable." The main limitations identified by alumni included that not all clinical solutions necessitate an engineering solution, despite the engineering focus of the class, and the lack of freedom to explore outside the students' field of study.

Discussion:

From the interviews, it's clear that BME 6301 and BME 6302 had a uniquely positive impact on trainees' graduate experiences. Beyond just the firsthand shadowing experience,

clinical immersion provides a unique opportunity to bolster engineering students' understanding of the clinical space.

Most alumni agreed that, beyond their experiences in the OR with surgeons, conversations with physicians in other settings were especially valuable for identifying provocative questions. Additionally, these courses provide a useful connection with physicians, with many trainees noting that their mentor in the class ended up being on their thesis committee. One student even mentioned that their connection to their mentor helped them get hired at their current job.

While the two-course sequence centers on activities that are more consistent with academic outcomes, many of the trainees working in start-ups and industry also found the program very useful for their work. Many of those working in start-ups reported needing to interact extensively with surgeons and physicians for their biomedical products and having this experience through the coursework was very helpful as they already came in with a good understanding of how most clinical spaces operate.

Many of the trainees generally reported a strong sense of engineering identity and self-efficacy for their work. While it was not the focus of this study, it is still important to mention as it might tie back to the self-efficacy instrument previously published [12].

The findings emphasize the importance of education innovation, in this case creating a unique learning opportunity that combines a hands-on experience with engineering principles. By showcasing the importance of interdisciplinary collaboration, this study proves to be a model for developing engineering courses that better prepare students through a holistic educational framework. This research paper serves as an example for institutions to attempt similar approaches, bettering students, professors, the medical community, and patient outcomes.

Though there are few participants each year in the two-course sequence, future alumni will be tracked and current alumni will continue to be interviewed to see if the current primary findings remain significant and to identify additional aspects of the courses that could be improved. Additionally, the research will be reviewed to identify possible opportunities for deeper exploration. A comparison study with alumni of the same BME graduate program who did not take this two-course sequence would also be instructive to better understand the effectiveness of preparing students for professional and academic success.

While the courses were highly impactful, alumni suggested areas for improvement: more shadowing opportunities and time to explore domains outside of their assigned field. In data not reported here, however, external program review offered a contraindication to this second potential area of improvement. The advisory board's experience was that if trainees had too diffuse an experience, the trainee would be less likely to have experiences with complications or varying complexity within a given specialty.

As metrics for immersion are considered, approaches must prepare graduate students to excel in both academic and professional status. The underlying premise is that clinical immersion programs play a vital role in equipping students with the necessary expertise to address real-

domain healthcare challenges and improve patient care. In this paper, the researchers introduce a relatively simple longitudinal assessment tool using a post-graduate surveying approach to establish the impact of immersion training in their career progression. While the metric provides insight and is a valuable step forward in assessment, it is undoubtedly incomplete. More evaluative tools are needed but we reiterate that immersion approaches must move beyond frameworks that only consider immersion experience density and must be aligned with appropriate metrics such as the career-impact metric reported here.

It is important to note that the courses are still relatively new, and the alumni sample size is small. With a small sample size, there is a potential for sampling bias. Furthermore, the alumni are in the early stages in their fields and careers, and therefore, the long-term effects of the two-course sequence remain to be fully assessed. Future studies could potentially analyze the same cohort later in their careers or conduct a similar study across multiple clinically immersive biomedical engineering programs to compare their long-term impacts. Additionally, future areas of research could include whether high- or low-density programs are more effective in achieving better outcomes of clinical immersion as graduate courses tend to have a lower density compared to undergraduate courses.

Conclusion:

This study's findings emphasize the significance of the BME 6301: Engineering in Surgery and Intervention — Provocative Questions, and BME 6302: Engineering in Surgery and Intervention — Clinical Interactions two-course sequence on professional development. Due to the hands-on clinical immersion within an engineering-focused program, these courses are uniquely designed to prepare graduate students for professions in academia, industry, and startups. The data collected stressed the impact of shadowing surgical procedures in the operating room, interacting with physicians, and engaging in discussions on translating engineering solutions in clinical settings. The outcome of these courses cultivated a strong sense of engineering identity and self-efficacy and overall sparked career success.

The two-course sequence, BME 6301 and BME 6302, serves as a model for other institutions to emulate, combining theoretical knowledge with practical application to equip students with the valuable skills to drive innovation in healthcare and improve patient outcomes.

Acknowledgement:

This research was supported by National Institute of Biomedical Imaging and Bioengineering of the National Institutes of Health under award #T32EB021937, the Vanderbilt Institute for Surgery and Engineering, and the Vanderbilt University School of Engineering. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

References:

[1] W. H. Guilford, M. Kotche, and R. H. Schmedlen, "A survey of clinical immersion experiences in Biomedical Engineering - Biomedical Engineering Education," *Biomedical*

Engineering Education, vol. 3, pp. 113-122, Apr. 2023. https://doi.org/10.1007/s43683-023-00107-5

[2] Carnegie Mellon University, “Graduate course catalog - biomedical engineering - college of engineering - Carnegie Mellon University,” Graduate Course Catalog - Biomedical Engineering - College of Engineering - Carnegie Mellon University, https://www.cmu.edu/bme/Academics/graduate-programs/Resources/catalog.html (accessed Dec. 13, 2024).

[3] “Biomedical engineering graduate courses, Biomedical Engineering and Mechanics | Virginia Tech, https://beam.vt.edu/graduate/biomedical/courses.html (accessed Dec. 13, 2024).

[4] E. A. Logsdon, R. Allen, N. J. Durr, and H. Nguyen, “Board #11: A team leader model for biomedical engineering design team project-definition training and scalable clinical observation (work in progress),” ASEE PEER Document Repository, https://peer.asee.org/board-11-a-team-leader-model-for-biomedical-engineering-design-team-project-definition-training-and-scalable-clinical-observation-work-in-progress (accessed Dec. 23, 2024).

[5] Use of a grant writing class in training Phd students - kahn - 2016 - traffic - wiley online library, https://onlinelibrary.wiley.com/doi/full/10.1111/tra.12398 (accessed Feb. 17, 2025).

[6] J. Ying, “The importance of the discussion method in the undergraduate business classroom,” Humanistic Management Journal, https://pmc.ncbi.nlm.nih.gov/articles/PMC7643722/ (accessed Feb. 17, 2025).

[7] S. V. Kotsis and K. C. Chung, "Application of the "see one, do one, teach one" concept in surgical training," (in eng), Plast Reconstr Surg, vol. 131, no. 5, pp. 1194-1201, May 2013.

[8] J. L. Cameron, "William Stewart Halsted. Our surgical heritage," (in eng), Ann Surg, vol. 225, no. 5, pp. 445-58, May 1997]

[9] M. Miga and R. Labadie, “A novel clinically immersive pre-doctoral Training Program for Engineering in surgery and intervention: Initial realization and preliminary results,” *Biomedical Engineering Education*, vol. 1, pp. 259-276, Jul 2021. https://doi.org/10.1007/s43683-021-00051-2.

[10] “Otter.ai,” Otter.ai, https://otter.ai/ (accessed Dec. 13, 2024).

[11] “Dedoose,” Dedoose, https://www.dedoose.com/ (accessed Dec. 13, 2024).

[12] Zhang, N., Klein-Gardner, S. S., & Miga, M. I., “Measuring Biomedical Engineers’ Self-Efficacy in Generating and Solving Provocative Questions about Surgery,” Paper presented at 2023 ASEE Annual Conference & Exposition, Baltimore, Maryland. June 2023. https://peer.asee.org/43565