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Surgineering: Curriculum Concept for Experiential Learning in Upper-Level Biomedical Engineering

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Abstract

Purpose: A strong foundation in the fundamental principles of medical intervention combined with genuine exposure to real clinical systems and procedures will improve engineering students' capability for informed innovation on clinical problems. To help build such a foundation, a new course (dubbed Surgineering) was developed to convey fundamental principles of surgery, interventional radiology (IR), and radiation therapy, with an emphasis on experiential learning,

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There were no human or animal studies conducted in this work.

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hands-on with real clinical systems, exposure to clinicians, and visits to real operating theatres. The concept, structure, and outcomes of the course of the first run of the first semester of the course are described.

Method: The course included six segments spanning fundamental concepts and cutting-edge approaches in a spectrum of surgical specialties, body and neurological IR, and radiation therapy. Each class involved a minimum of didactic content and an emphasis on hands-on experience with instrumentation, equipment, surgical approaches, anatomical models, dissection, and visits to clinical theaters. Outcomes on the quality of the course and areas for continuing improvement were assessed by student surveys (5-point Likert scores and word-cloud representations of free response) as well as feedback from clinical collaborators.

Result: Surveys assessed four key areas of feedback on the course and were analyzed quantitatively and in word-cloud representations of: (1) best aspects (hands-on experience with surgeons); (2) worst aspects (quizzes and reading materials); (3) areas for improvement (projects, quizzes, and background on anatomy); and (4) what prospective students should know (a lot background reading for every class). Five-point Likert scores from survey respondents (16/19 students) indicated: overall quality of the course 4.63 ± 0.72 (median 5.00); instructor teaching effectiveness 4.06 ± 1.06 (median 4.00); intellectual challenge 4.19 ± 0.40 (median 4.00); and workload somewhat heavier (62.5%) compared to other courses. Novel elements of the course included the opportunity to engage with clinical faculty and participate in realistic laboratory exercises, work with clinical instruments and equipment, and visit real operating theaters. An additional measure of the success of the course was evidenced by surveys and a strong escalation in enrollment in the following year.

Conclusions: The Surgineering course presents an important addition to upper-level engineering curricula and a valuable opportunity for engineering students to gain hands-on experience and interaction with clinical experts. Close partnership with clinical faculty was essential to the schedule and logistics of the course as well as to the continuity of concepts delivered over the semester. The knowledge and experience gained provides stronger foundation for identification of unmet clinical needs and ideation of new engineering approaches in medicine. The course also provides a valuable prerequisite to higher-level coursework in systems engineering, human factors, and data science applied to medicine.

Keywords

biomedical engineering; curriculum; surgery; interventional radiology; radiation therapy

1. INTRODUCTION

Informed innovation in biomedical engineering relies on an understanding of real clinical problems, the context within which such problems arise, and the stakeholders affected by potential engineering solutions. Such understanding is most often gained – if it is gained at all – via meaningful engagement in real clinical environments and interaction with clinical experts. Recognizing the value of hands-on, experiential learning and motivated by the desire to bring engineering students to a more profound understanding of clinical problems, a new course series (dubbed “Surgineering”) was offered for the first time in our department

(Biomedical Engineering, Johns Hopkins University) in academic year 2018–19. The course emphasizes fundamental principles in medical interventions and provides a diversity of hands-on learning activities enabled by close collaboration with clinical experts at our institution. The course is complementary to coursework and projects in biomedical design, targeting students in the Masters of Science and Engineering (MSE) Program and open to senior undergraduates and PhD students.

The term “Surgineering” was coined in the scientific literature by Feussner et al.¹ in recognizing the tremendous potential for more meaningful engagement of engineers with clinical partners in identifying major un-met, un-served, and/or un-articulated clinical needs. They rightly noted that the recognition of meaningful clinical needs is best understood by the clinician, whereas major technology innovation requires the deep technical expertise of engineers rigorously trained in math, physics, computing, and quantitative biomedical science. Rather than fairly straightforward interdisciplinary collaboration in which the surgeon is called upon to evaluate a developing technology in hopes that it meets a clinical need, a more interdisciplinary approach promises a more productive path that starts with engineers and surgeons working together to identify clinical needs and developing solutions driven by that need.

As detailed in this manuscript, a new one-year Surgineering curriculum was developed at our institution motivated by such interdisciplinary approach. The first semester of the series (580.740 Surgery for Engineers) provided introductory-level content and hands-on experience with the principles and practice of interventional medicine – including a spectrum of open and minimally invasive surgical approaches as well as procedures in interventional radiology (IR) and radiation therapy. Specific course segments included general surgery, orthopaedic surgery, otolaryngology – head and neck surgery, neurosurgery, interventional radiology (IR), and radiation therapy. Each segment addressed concepts of pertinent anatomy, surgical instrumentation, and interventional approach, led by a clinical expert (surgeon, radiologist, or radiation oncologist) working closely with the course director (a biomedical engineer). Background material delivered prior to each class included reading and videos, and each class involved a brief lecture followed by extensive hands-on demonstrations, laboratory activities, and visits to clinical areas at our institution. Students were expected to demonstrate a synthesis of concepts from lectures and background materials in quizzes and higher-level themes via two course projects. Drawing from 580.740 as a prerequisite, the second semester (580.750 – Surgineering: Systems Engineering and Data Science in Interventional Medicine) included deeper clinical immersion, lectures on systems engineering, human factors, and data science, and team projects relating to patient safety, data capture and curation, predictive modeling, and workflow.

The course concept is motivated by experience and conviction that a stronger fundamental understanding and exposure to real clinical systems and expertise will provide a stronger foundation for informed innovation in biomedical engineering. The initial run of the course provided an initial step in improving such foundations in upper-level engineering curricula, as detailed below in the principles, methods, and results obtained following the first run of the first segment (580.740 Surgery for Engineers).

2. METHODS AND MATERIALS

2.1 Class Format

Classes were held twice per week for 90 minutes each (Tuesdays and Thursdays, 8:00 – 9:30 AM) for one semester (26 classes total). Background materials assigned prior to each class consisted of 1 or 2 basic review articles and 1 or 2 videos covering introduction to a particular specialty. Review articles generally covered basic principles and aspects of history and state of the art for a particular interventional technique. Videos freely available online featured demonstrations and/or actual surgeries and were an especially good means of conveying surgical techniques. A collection of “Anatomy Notes” were developed to summarize pertinent anatomy for each class (the heart, brain, ear, spine, etc.) – each a one-page illustrative diagram with comments highlighting essential anatomy.

Each class began with a 10-minute quiz on background materials, followed by a brief lecture by clinical faculty on particular aspects of a given specialty or procedure (nominally 15 min, some up to 25 min). The remaining ~1 hr of class was dedicated to group activities in an operating room (OR) laboratory and/or visits to clinical areas – each involving hands-on activities with real clinical systems, instrumentation, equipment, and models (phantoms or cadavers) pertinent to a particular medical procedure. Depending on the topic for hands-on activities, the class was typically divided into 2–4 groups led by the course director, a clinical faculty person, a clinical resident or fellow, and a teaching assistant (PhD student in biomedical engineering).

2.2 Environment and Experiential Learning.

Classes were held in a standing workbench classroom and OR Labs located at the Carnegie Center for Surgical Innovation (<http://carnegie.jhu.edu>) at Johns Hopkins Hospital. Photographs of example classroom setups are illustrated in the Appendix. Several classes were held at the adjacently located Minimally Invasive Surgical Training and Innovation Center (MISTIC) Facility. Numerous visits to clinical theaters at Johns Hopkins Hospital were led by clinical faculty, including operating rooms (ORs), IR suites, and radiation therapy treatment rooms.

Green scrubs were assigned to each student during the first class, and students were expected to arrive to class in scrubs for all subsequent classes. Regularly wearing scrubs improved safety in hands-on activities (many including anatomical models and/or cadaver dissection, intraoperative imaging, surgical instrumentation, and other equipment), ensured acceptable attire during visits to clinical areas, and promoted a team experience. As illustrated in figures in the Appendix, chairs were removed from the classroom (allowing exception by request) to promote interactivity, better ensure attention in early morning classes, and convey an aspect of real-life experience of clinical activity requiring extended periods on one’s feet.

2.3 Clinical Faculty.

The schedule and scope of topics covered in the course are summarized in Table 1. Approximately 20 clinical faculty contributed in some way to the course – providing a brief

seminar, guiding students in hands-on activities, and working closely with the course director on subject matter to ensure continuity across such a broad spectrum of topics. Several vendors also provided equipment to the course (without cost) and participated in some of the hands-on activities involving real clinical equipment. The success of such a schedule relied upon the expertise and good will of collaborating clinical faculty, and a number of means to maintain and sustain the curriculum in the longer term are noted in Discussion.

2.4 Enrollment and Certifications.

The course targeted graduate-level (MSE) engineering students, and senior-level undergraduates and PhD students were admitted upon approval from the instructor. Enrollment was limited to 20 students due to space and resources in hands-on / lab activities. Audits were not allowed. While there were no prerequisites for the course, students were required to complete the following certifications online by the end of the second week: *Bloodborne Pathogens*, *Fluoroscopy Refresher*, and *Patient Privacy for Workforce Members*. Each learning module was available from our institution.

2.5 Class Projects.

Two projects exercised higher-level synthesis of ideas encountered in class. Project #1 was a written report and oral presentation performed in teams of two. In each case, students formed a “Position Statement” on a controversial topic in interventional medicine and defended their position in an oral presentation. The report and presentation provided critical analysis of the topic, including: background, counter-arguments, a clear statement of position, and references. Reports were limited to 3–5 pages, and presentations were 5-minute oral presentation with slides plus 10 minutes Q&A and defense of the position. In addition to his/her own written Position Statement, each student was assigned to critique two other position statements during the oral presentations. Several clinical collaborators attended the presentations and participated in the discussion and debate.

Project #2 involved hands-on hardware development and a computer interface to build one’s own surgical navigation system. Projects were conducted in teams of 3, and a laboratory benchtop was assembled from systems collected from the course director’s laboratory. One of three projects was randomly assigned to each team, each exercising a different surgical tracking technology, anatomical context, and guidance task. A computer workstation (Dell Precision T7500) with 3D Slicer software²) was interfaced with the bench, and a collection of surgical instruments and rigid-body dynamic reference frames appropriate to each tracker were provided.

Project 2A involved an optical video surgical tracker (MicronTracker, Claron, Toronto ON) and a simple spine phantom suitable to x-ray and CT imaging (Sawbones, Seattle WA). The teams configured a tracked pointer and screwdriver for CT and video navigation of spine pedicle screw placement.

Project 2B involved an infrared surgical tracker (Polaris Vicra, NDI, Mississauga ON) and a lumbar punch phantom (CIRS, Cleveland OH) allowing needle insertion. The lumbar

phantom was imaged in CT and MRI for lumbar punch, and teams configured a tracked needle emulating spinal injection in a pain management procedure.

Project 2C involved an electromagnetic (EM) surgical tracker (Polaris Aurora, NDI, Mississauga ON) and an abdominal phantom (CIRS, Cleveland OH) presenting simulated lesions and allowing needle insertion. The phantom was imaged in CT and ultrasound, and teams configured trackable needles to simulate targeting and biopsy of a simulated lesions.

In each case, teams configured a set of 3D Slicer modules for image registration, navigation, and display, measured the accuracy of the tracking system (target registration error,³ TRE), and wrote a report describing their solution and relating to concepts learned regarding real clinical practice and workflow.

2.6 Extra Credit.

Three extra credit assignments provided opportunity to think beyond course content and earn extra points toward the final grade.

Extra Credit #1 stemmed from the first week of class in which students learned the basics of needle, suture, and wound closure. Each student was given a collection of suture, needles, and a suture pad and had 3 weeks to deliver a variety of sutures to the practice pad and turn in their best product. Each suturing pad was scored by 5 surgical residents in terms of quality of sutures (distance between sutures, distance from skin edge, knots square to wound, tight knots) and variety of sutures delivered (single interrupted, running, mattress, subcuticular, etc.).

Extra Credit #2 further motivated the students to proactively contact clinical faculty for visitation to clinic areas and/or the operating theater. Each visit was scheduled by the student with any clinical faculty participating in the course, and extra credit was based upon documentation in a 1–3 page report describing the procedure(s), workflow, technologies, and challenges observed.

Extra Credit #3 was a 1-page report evaluating the advantages and disadvantages of a specific topic that was covered more deeply in the middle segment of the course: open approach versus minimally invasive spine surgery, including factors relating to outcome and cost. This specific topic was selected to give all students a deeper dive on a shared clinical topic (whereas Extra Credit #2 was diverse across many clinical areas) and promote critical thinking on an important clinical area with a large and growing market and challenges to quality outcomes. The topic is anticipated to change from year to year.

2.7 Materials and Budget.

In addition to materials gathered from the course director's laboratory, a budget of \$7500 was available from our Master's Program. Major cost categories were supplies, personal protective equipment (PPE), instrumentation, and specimens. The budget also covered food and beverages for sessions (e.g., Project #1 presentations) held outside normal class time. Much of the instrumentation procured for the first run of the course is reusable from year to year. Contributing faculty were not directly paid for their participation, and a number of

alternative methods to sustain participation in the longer term are mentioned in Discussion. It is worth noting the considerable *pro-bono* contributions from vendor representatives who loaned supplies and instrumentation for particular classes – e.g., spinal instrumentation, orthopaedic implants, RF and cryoablation systems, and a VR system. The cost of such supplies and participation is likely well beyond what could be supported by our academic program, and the course relies on such *gratis* contributions and good will.

2.8 Grades.

The final grade was determined as follows: Attendance / Participation (10%); Quizzes (30%, 17 quizzes in total; reject lowest score); Project #1 (30%); and Project #2 (30%). Extra Credit #1 earned up to 5 points applied toward Quizzes, and Extra Credit #2 and #3 each earned up to 5 points applied toward Projects.

3. RESULTS

3.1 Enrollment and Withdrawals

Enrollment was capped at 20 students, and approximately 26 students attended during the first 2 weeks of the course. (As noted in Discussion, the second run of the course met the enrollment cap within the first days of registration plus a waitlist of more than 30 students, presenting a challenge to future scale and scheduling.) Total enrollment in the course reduced to 19 students within 2 weeks, including 1 undergraduate senior, 14 MSE students, and 4 PhD students – all of whom completed the course.

3.2 Topics and Clinical Faculty Engagement

Clinical faculty from several departments contributed significantly to the course, as summarized in the topics summarized in Table 1. The challenges associated with “team-taught” courses were recognized at the outset; however, the breadth and depth of material is likely beyond the knowing of any individual or small team. Close coordination and engagement with clinical faculty was therefore essential to the course. In the month prior to class, the course director met individually with each clinical faculty member to discuss the concept, structure, and goals of the course and work together in outlining the content of each class. Prior to each class, the course director met again with the faculty person to finalize particulars of the class, including specialized lab / demo equipment, etc.

Example classroom setups and hands-on activities are illustrated in figures in the Appendix, covering six main segments of the course, summarized as follows.

Segment 1: Introduction and Basic Principles.—Following introduction and overview of the course, the course director, a general surgeon, surgical resident, and anesthesiology technologist covered principles of antiseptic surgery, scrubbing in, negative-pressure wound dressing, basic surgical instrumentation, cautery, suturing, anesthesia, and patient monitoring. Each involved a brief didactic session followed by more extensive hands-on, for example: scrubbing in at a scrub station; preparing a wound vac (applied to watermelon models); cautery (in chicken breast); suturing (bananas and a take-home suture

pad for extra credit); an array of basic surgical instrumentation, airway access on a training phantom; and demonstration of a gas cart.

Segment 2: General, Thoracic, and Cardiac Surgery.—A series of 5 classes were held in the MISTIC Facility at Johns Hopkins Hospital, led by a general surgeon in coordination with a thoracic surgeon, a cardiac surgeon, and a gynecological surgeon, each assisted by a general surgery fellow. Following a brief lecture on each topic, hands-on labs included guided activities in simulators and cadavers on laparoscopic surgery, bronchoscopy, cardiac dissection, and use of the DaVinci robot (Intuitive, Sunnyvale CA) for prostatectomy and hysterectomy.

Segment 3: Intraoperative Imaging and Navigation.—Three classes led by the course director covered principles of intraoperative imaging, registration / coordinate transforms, and navigation. Seminars were somewhat extended beyond the usual 15–25 min to cover technical engineering principles (e.g., x-ray and ultrasound imaging, surgical trackers, etc.), but each class maintained hands-on activities, including: use of an ultrasound system (ECube, Alpinion, Seoul Korea) with various phantoms; observation of a fluoroscopic C-arm from behind a shielded barrier; and work with a tracking system (StealthStation, Medtronic, Littleton MA). These classes also provided the background necessary to Project #2.

Segment 4: Spine, Neuro, and Orthopaedic Surgery.—Seven classes covered basic principles, hands-on labs, and OR visitations in spine surgery, neurosurgery, and orthopaedic surgery. The spine surgery classes covered aspects of pedicle screw placement and surgical navigation, including hands-on use of navigated instruments. The neurosurgery classes included overview of tumor surgery, neuroendoscopy, neuroelectrode placement, and MRI-guided thermal therapy. The orthopaedic surgery classes covered trauma surgery (including fracture reduction and fixation) as well as joint replacement. Visits to clinical theatres included neurosurgery ORs for robot-assisted surgery and MR-guided surgery.

Segment 5: Interventional Radiology.—Four classes focused on interventional radiology, including body, neuro, and musculoskeletal interventions. The body interventions class included hands-on activities for ultrasound-guided biopsy (olives embedded in turkey breast) as well as cryo-ablation and RF ablation (in bovine liver). Students also learned to handle embolization devices (coils, plugs, and particles) as well as a variety of catheters. The neurointerventions class included a hands-on trainer in neurovascular clot removal, and the musculoskeletal interventions class included ultrasound and x-ray guided needle placement in joints (phantoms and cadaver specimens). Visits to clinical theatres included IR suites for CT and MR guided interventions.

Segment 6: Radiation Oncology.—The final segment involved 3 classes in radiation therapy. The first covered principles of radiation biology and radiotherapy treatment planning, including hands-on planning with a real clinical treatment planning system for 3D conformal planning of prostate cancer treatment. The second covered principles of image-guided radiotherapy, including tours of linear accelerator systems in the Department of

Radiation Oncology. The third included principles of brachytherapy, including an overview of applicators and an HDR suite for CT-guided gynecological brachytherapy.

3.3 Projects

Project #1 (Position Statement).—A summary of the position statements on controversial topics selected by students is shown in Table 2. Written reports were circulated weeks in advance of oral presentations, and each student provided counter-argument during presentations. Clinical faculty were also invited to attend, and their contributions to the discussion were especially stimulating and insightful.

Project #2 (Navigation System).—As described in Methods, the second project entailed configuration of 3D Slicer software modules with a variety of surgical tracking systems and phantoms. Each included interface to a surgical tracker (video, infrared, or electromagnetic), registration of image data for a particular anatomical phantom, configuring a tracked device to target anatomy in the phantom, and evaluation of targeting error. Positive aspects of the projects included hands-on experimentation with real systems pertinent to state-of-the-art image-guided surgery. Although most of the software elements were pre-packaged, many students did not have strong background in C++ programming to configure the system well, and the material covered in the three classes of Segment 3 (Table 2) was likely not enough to providing sufficient background. Students who had previously taken courses on computer-integrated surgery (covering principles of geometric transforms, point-based registration, etc.) were much more comfortable with the project. Students also felt considerable time pressure completing the project during Finals Week. As discussed below, future runs of the course will better integrate and pace the lab projects more regularly throughout the semester and further reduce the depth of prerequisite knowledge in C++ programming.

3.4 Materiel and Budget

A summary of supplies, personal protective equipment (PPE), instrumentation, specimens, and food (for oral presentation sessions held outside normal class time) is shown in Table 3, along with expenditures. Approximately one-third of the total cost in the first run of the course amounts to supplies or equipment that are reusable from year to year. Other costs not directly accounted include a considerable amount of equipment borrowed from the course director's laboratory (e.g., trackers and phantoms for Projects #1 and #2), demonstration models provided at no cost by vendor representatives, a graduate student Teaching Assistant, and the generous contribution of time from clinical faculty.

3.5 Final Grades

Grades were assigned according to scores on quizzes, projects, and attendance / participation as detailed above. Grades among 19 students were as follows: 1 A+, 6 A, 2 A–, 2 B+, 7 B, 0 B–, 1 C+, 0 C, 0 C–, 0 D, 0 F, and 0 W.

3.6 Student Survey Results

A summary of course evaluations completed by students (16/19) is shown in Table 4. Final grades were communicated to students before the deadline for course evaluation. (I.e.,

students were aware of their final grade when completing the survey.) Overall, the quality of the course was judged to be high (4.63 ± 0.72 compared to the departmental average of 3.82). Additional evaluation of the instructor effectiveness, TA, feedback, and workload is summarized in the Table.

Free response comments in the survey queried the following: (a) Best aspects of the course; (b) Worst aspects of the course; (c) What would most improve the course; and (d) What prospective students should know. Figure 1 shows word-cloud representations of the free response for each. For question (a – best aspects), the word cloud representation reflects students' enthusiasm for hands-on experience with actual surgeons. Question (b – worst aspects) reflects areas for improvement with quizzes, the amount of reading materials, and projects. Strategies for improvement are described below – consistent with the word-cloud representation of responses to question (c – improvements). The responses to question (c – prospective students) suggest that students should be prepared for a fairly heavy load of consistent effort in readings and classes.

4. DISCUSSION AND CONCLUSIONS

Leveraging an environment of collaborative clinical partnership, motivated by the principle that firm grounding in clinical fundamentals promotes more meaningful engineering innovation, and recognizing the potential of an interdisciplinary “Surgineering” approach as expressed by Feussner et al.¹, the curriculum described in this work is an important step in educating engineers whose work toward major technological advances will be clearly driven by the recognition of genuine clinical needs. Overall, the course (580.740 Surgery for Engineers) is believed to be a valuable addition to the upper-level engineering curriculum, providing students with a rare level of hands-on experience and interaction on topics of interventional medicine with expert clinicians.

The course brings engineering students together with expert clinicians in an environment of educational and clinical resources at our institution that is beyond that of traditional classroom experience. It requires generous, willing partnership of clinical collaborators and could not exist without their expert contributions. The effort associated with directing the course is high – requiring coordination of busy clinical schedules, expensive equipment, resourcefulness in obtaining supplies and instrumentation within a realistic budget, and preparation of backup plans for last-minute cancellations and clinical emergencies. The class requires a similar level of dedication and effort from its students – arriving early at the hospital, in scrubs, and involving a fairly large workload of background reading and project assignments. The outcome, however, appears to be worth the effort: students remarked positively on the unique opportunity to gain first-hand experience and interaction with practicing clinicians, giving them a more solid foundation in clinical fundamentals as an important part of their foundation as biomedical engineers.

Based on observations and feedback from the clinical faculty and students in the first run of the course, a number of potential improvements are recognized and are being implemented for future runs of the course. First is the need to maintain engagement and willing partnership of clinicians in order to sustain the course in the longer term. Their generous

giving of time and expertise (even if just 1 or 2 classes per clinician to distribute the load) is a priceless commodity that likely could not be met in simple monetary terms. (A rough estimate suggests that the cost associated with such high-level personnel for a total of ~40 contact hours would easily exceed the total budget for the course.) The need to ensure value to participating clinical faculty and sustain their willing partnership is key. A number of mechanisms are being considered, including specific efforts to: connect clinical faculty with engineering students for volunteer clinical / research internship opportunities; connect clinical faculty with engineering design teams (e.g., senior capstone or MSE-level design projects) on topics of mutual interest; communicate the contributions and performance of contributing faculty to clinical department Chairs; accordingly noting teaching effort in one's curriculum vitae for reporting of annual activities and performance; conduct an annual appreciation event (dinner) to show gratitude on behalf of the engineering department; engage clinical faculty in strategic planning for departmental collaboration; and consider courtesy cross-appointment where appropriate. Some or all of these measures are likely important to long-term sustainability of the curriculum – as is a commitment from institutional leadership as to its value and importance. At the time of writing, all of the clinical faculty involved in the first run of the course have agreeably committed their schedules to the next run of the course. Additional areas of clinical specialty that may be incorporated in future runs of the course include ophthalmology (e.g., retinal surgery) and physical rehabilitation.

Quizzes were also identified as an area in need of improvement. Students did not like quizzes delivered each class, although doing so helped to ensure that students arrived on time and had covered background materials. However, the quiz content was also identified as a problem – too difficult and too much anatomy to learn, resulting in considerable anxiety. The problem was identified within the first few weeks of the course (at which time quizzes were written primarily by the TA), and the course director worked more directly with the TA to draft quiz content. Still, students found it difficult to prepare for quizzes given such broad background materials, and they were especially challenged to learn anatomy. Possible exceptions to this were the BME PhD students who had taken Gross Anatomy in the Medical School during their first year of PhD coursework. A set of one-page “Anatomy Notes” summarizing key aspects of pertinent anatomy was drafted for each segment, but the level of detail in memorization did not resolve the issue. While quizzes are a good mechanism to ensure attendance and preparation, future offerings will lighten the difficulty to the level of a basic check of understanding on background materials. More importantly, quiz content should not emphasize a regurgitation of memorized material; rather, quizzes should reflect high-level principles as a basic check on comprehension and emphasize engineering principles (e.g., technologies and areas of future innovation) wherever possible.

Potential improvements to the overall schedule are also recognized. Project #1 was due late in the semester to give students time to survey many possible areas of controversial topics and to exchange reports for knowledgeable debate. However, this created a time-crunch with the Project #2 due date. We anticipate changing the second project to a series of smaller-scale labs on imaging and navigation that can be carried out during the semester with a lighter overall workload, allowing the position statement on controversial topics to be delivered as a final project at the end of the semester.

The background knowledge assumed for Project #2 was a bit high (e.g., programming in C++ and an understanding of coordinate transforms). Such topics are core to other coursework (e.g., Computer-Integrated Surgery) and were therefore not covered in detail in this course to avoid overlap and redundancy. Students who had taken such a previous course had no problem with these concepts, so the course might be considered for prerequisite. Additionally, Project #2 will be spread in future runs of the course into a series of lighter-duty “labs” throughout the semester (cf., integrating a full navigation system as final project) involving smaller tasks. A series of recitations will also be offered outside normal class hours to convey concepts beyond that in class in Segment 3 (imaging and navigation).

Finally, the course provided a valuable prerequisite to a second course in development (580.750 Surgineering: Systems Engineering and Data Science in Interventional Medicine), which ran in the following semester. The top 10 students were invited to enroll in 580.750, and 8 students accepted the invitation. In its first run, 580.750 involved deep clinical immersion and projects involving systems-level analysis, patient safety, workflow, and human factors. Example projects arising from the course included: workflow modeling for MR-guided neurosurgery; predictive modeling from anesthesia cart time series data; automatic prediction of OR status from computer vision systems; and natural language processing as an assistant to information retrieval from the electronic medical record (EMR). Such insightful projects at levels relating to higher-level systems, health information, and patient safety / workflow are consistent with the motivating principle that a stronger foundation in fundamentals of interventional medicine will enhance informed innovation, in this case at the level of systems and data (cf., devices) that would be difficult to appreciate without such exposure to real clinical operations.

Leveraging an integrated environment for teaching and clinical practice along with interdisciplinary expertise in engineering and interventional medicine, the “Surgery for Engineers” course provides an important addition to upper-level curriculum in biomedical engineering and valuable experience for students. Relying on close collaboration with clinical colleagues, the knowledge and experience gained in this course is believed to provide a stronger foundation in fundamentals of interventional medicine, systems and technologies, and clinical operations that should enable better informed recognition of real clinical challenges and promote meaningful ideation of new biomedical engineering advances. The course appears to be a success. The second run of the course (2019–20) was oversubscribed by a factor of 3x upon opening of online enrollment (~60 students enrolled, compared to the enrollment cap of 20).

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APPENDIX

The following photographs illustrate a variety of activities in the course, including a number of experiential, hands-on elements – for example: students regularly required to wear green scrubs; brief didactic introduction to each topic followed by hands-on experience with instrumentation and phantoms / cadavers. Several classes gave exposure to real clinical systems in the operating theatres at our institution. (Photographs of students and staff are permitted for use in publications within institutional policy on Photography and Film Rights.)

Figure A.1.

Example classroom setup: wound closure. Six stations on the principles of wound closure, each with a granular sponge wound pack and watermelon (a common model for practicing negative pressure wound treatment). The classroom area is located in the Carnegie Center for Surgical Innovation at Johns Hopkins Hospital.

Figure A.2.

Example classroom setup: suturing. Individual stations for the principles and tools of suturing. A variety of needles and sutures for distinct purpose and tactile experience. Bananas are a common model for suturing. The class also gave important introduction to handling of sharps.

Figure A.3.

A general surgeon introduces principles and tools of laparoscopic surgery and energy delivery (monopolar and bipolar cautery). Cautery systems and chicken breast models can be seen at each station.

Figure A.4.

A general surgeon teaches principles and tools of laparoscopy in the MISTIC Facility at Johns Hopkins Hospital.

Figure A.5.

A thoracic surgeon teaches lung anatomy and bronchoscopy in an ex vivo porcine lung.

Figure A.6.
Students learn cardiac anatomy and dissection.

Figure A.7. Students gained introduction to principles and practice of robotic surgery, including the Da Vinci robotic surgery system.

Figure A.8.

Students learn a broad spectrum of general surgical instrumentation and specialized tools – e.g., spinal instrumentation and navigation. Here, a spine surgeon introduces principles and hands-on practice in pedicle screw placement. Students gained familiarity with both open and minimally invasive approaches.

Figure A.9.

Visits to the neurosurgical ORs at Johns Hopkins Hospital provided exposure to real clinical systems for surgical navigation and robotic assistance. Here, a neurosurgeon gives hands-on introduction to stereotactic systems and robotics for brain tumor surgery, thermal ablation, and electrode implants.

Figure A.10.

Otolaryngology surgeons teach principles of ENT surgery and oversee hands-on exercises in cadaveric specimens for cochlear implant.

Figure A.11.

An orthopaedic surgeon shows the use of a virtual reality system for training in trauma surgery and joint replacement procedures

Figure A.12.
Students worked hands-on with total knee replacement implants and instrumentation in sawbones knee phantoms.

Figure A.13.

A musculoskeletal radiologist shows students the use of ultrasound in accessing joints in the lumbar spine and extremities for biopsy or pain management.

Figure A.14.

An interventional radiologist teaches the technology and techniques of ultrasound-guided biopsy. Students also visited interventional radiology suites for MRI and CT guided procedures.

Figure A.15.

Application specialists give an overview of a cryoablation system for freezing liver tumors. In the foreground is a bovine liver for illustrating tissue ablation and the formation of the iceball.

Figure A.16.

Following seminars and background reading on the essentials of radiobiology, radiation therapy, and treatment planning, a tour to Radiation Oncology gave a first-hand look at systems and workflow in image-guided radiation therapy.

Figure A.17.

A radiation oncologist shows the tools and techniques for CT-guided and MR-guided gynecological brachytherapy.

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Figure 1. Word-cloud representations of free response surveys on: (a) Best aspects of the course; (b) Worst aspects of the course; (c) What would most improve the course; and (d) What prospective students should know.

Table 1.

Summary and schedule of topics covered in the course.

Class	Topic
1	OR layout and the sterile core. Who's who in the OR. Principles of antiseptic surgery. Scrubbing in. Gloves, gown, and PPE. Wound vac preparation with watermelon models.
2	Surgical instrumentation: the basic instrumentation tray. Cautery-monopolar and bipolar-with chicken breasts. Suture, needles. Hands-on suturing with bananas and suture pads.
3	Principles of anesthesia. The gas cart and patient monitoring. Airway access with an anatomical model.
4	Principles of general Surgery. Laparoscopic tools. Abdominal anatomy. Hands-on laparoscopy in simulation trainers and in cadaver.
5	Laparoscopic approach and suturing. Introduction and hands-on with the Da Vinci robot.
6	Principles of thoracic surgery. Thoracic anatomy. Hands-on bronchoscopy in training phantom and porcine lung.
7	Principles of cardiac surgery. Cardiac anatomy. Hands-on dissection of the heart.
8	Principles of urological / gynecological surgery. GI/GU pelvic anatomy. The Da Vinci robot - hysterectomy. Hands-on in training models.
9	Physics of medical imaging. Intraoperative imaging systems. Hands-on ultrasound, fluoroscopy, and cone-beam CT with anatomical models.
10	Principles of computer-integrated surgery. Point-set affine / rigid transformation. Application to surgical navigation. Infrared, EM, and optical tracking systems.
11	Principles of minimally invasive spine surgery navigation. Navigated spinal instrumentation. Hands-on with StealthStation in phantom.
12	Principles of orthopaedic spine surgery. Open approach. Spinal anatomy. Deformity correction. Hands-on pedicle screw instrumentation in sawbones.
13	Principles of neurological spine surgery. Minimally invasive approach. Hands-on with navigation and surgical robotics.
14	Visit to clinical OR. Intraoperative imaging (cone-beam CT) and robotics (Excelsius) in spine surgery.
15	Principles of brain tumor surgery. Anatomy of the brain. Neuroendoscopy. MRI guidance. Thermal ablation. Visit to clinical OR.
16	Principles of ENT Surgery. Anatomy of the ear and sinuses. Hands-on labs in cadaver: cochlear implant and endoscopic skull base surgery.
17	Principles of orthopaedic trauma surgery. Anatomy of the pelvis. Hands-on K-wire placement in sawbones models and cadaver.
18	Principles of joint replacement surgery. Anatomy of the knee. Hands-on total knee replacement in sawbones.
19	Principles of interventional radiology (IR). Introduction to body IR. Visit to IR suites. CT and MR guidance.
20	Principles of ablation (chemo, RF, and cryo) and biopsy. Biopsy instrumentation. Hands-on RF and cryo ablation in bovine liver. Ultrasound-guided biopsy in phantom.
21	Principles of neuro-interventional radiology. Neurovascular anatomy and pathology. Stroke management. Hands-on clot retrieval in training phantoms.
22	Principles of musculoskeletal IR and pain management. Hands-on needle placement (ultrasound and CT) in cadaver. Visit to hybrid MR-CT guidance suite.
23	Principles of radiation therapy and radio-biology. Hands-on treatment plan optimization (prostate IMRT).

Class	Topic
24	Principles of image-guided radiation therapy (IGRT). Visit to medical linear accelerators.
25	Principles of brachytherapy - LDR and HDR. Visit to HDR brachytherapy suite.
26	Project #1: Position Statements. Presentations and Counterargument.
Finals	Project #2: Build a Surgical Navigation System. Demo tests on Surgical Tracking Bench.

Table 2.

Summary of “position statements” selected by students (working in teams of two) for Project #1.

Team	Position Statement / Controversial Topic
1	“The Use of Live Animals Is an Invaluable Component of Surgical Education.”
2	“Customizable Orthopedic Implants Do Not Provide a Significant Advance over Conventional Implants”
3	“Robotic Surgery Represents a New Standard of Care for Minimally Invasive Hysterectomy”
4	“The Case against Robotic Thyroidectomy”
5	“Neuroendoscopy is Preferable to Craniotomy for Brain Tumor Surgery”
6	“The Risks Associated with Lumbar Fusion Outweigh the Benefits for Patients with Non-Specific Chronic Back Pain.”
7	“Bariatric Surgery Is Less Effective Than Behavioral Modification.”
8	“Radical Prostatectomy is Superior to Watchful Waiting.”
9	“Therapeutic Hypothermia is Effective and Beneficial to Treatment of Spinal Trauma.”

Table 3.

Summary of supplies, instrumentation, and costs for the first-run of the course.

Category	Description / Examples	Cost
Supplies	Scrub brush kits. VAC GranuFoam Dressing. Suction Canisters w/ tubing. Sharps containers. Sterile drapes and pads. SureFit Dual dispersive electrodes. 5 disposable bovies. Suture (Prolene 5-0 / 3-0 Monocryl / VCL 3-0 CT1 / Silk 3-0). Needles (24 Mixed Pack). 22 Pack (12 Pcs) Mixed Training Suture Threads with Needles. Medium 3-Layer Suture Pads. Endo Gia Staplers × 6. ET Tube × 2. Watermelons × 6 (wound closure). Bananas × 20 (suturing). 2 Turkeys & Olives (needle biopsy). Bovine livers (×2). Gelatin (ultrasound phantoms). Argon Gas tanks (cryoablation)	\$4,980
PPE	Gloves. Coveralls. Hair nets. Caps. Masks. Shoe covers. Green scrubs	\$364
Instrumentation	Forceps, fine, curved 4.5 / Forceps Medium, Curved Serrate / Forceps Cover Glass Flat / Forceps Medium Fine Straight Scapel #10 / Scalpel Handle #3 / Metzenbaum, Curved 7" / Metzenbaum, Straight, 5 3/4 Metzenbaum-Lahey Phys. Grade / Straight. 5 1/2 Scissors / Dissecting, Mayo, Curved 6.75 / Dissection, Straight Scissors Mayo Dissecting, Physician Grade Scissors / Surgical Scissors WL / Sharp-Point Surgical Scissors	\$842
Specimens	Porcine Lungs (× 2). Hearts (×4). Stomach (×1). Heads (×3, lightly fixed cut at sternal notch).	\$977
Catering	Project #1 Presentations (Breakfast ×15) Project #1 Presentations (Dinner ×15)	\$267
Total		\$7,430

Table 4.

Summary of course evaluations.

	(5) Excellent	(4) Good	(3) Satisfactory	(2) Weak	(1) Poor	Mean	StDev	Median
Overall quality of the course (Dept. level)	75.00%	12.50%	12.50%	0.00%	0.00%	4.63 (3.82)	0.72 (1.01)	5.00 (4.00)
Instructor teaching effectiveness (Dept. level)	43.75%	31.25%	12.50%	12.50%	0.00%	4.06 (4.02)	1.06 (1.01)	4.00 (4.00)
Intellectual challenge (Dept. level)	18.75%	81.25%	0.00%	0.00%	0.00%	4.19 (4.21)	0.40 (0.86)	4.00 (4.00)
Teaching assistant (Dept. level)	31.25%	31.25%	31.25%	6.25%	0.00%	3.88 (4.23)	0.96 (0.96)	4.00 (4.00)
	Agree strongly	Agree somewhat	Neither agree nor disagree	Disagree somewhat	Disagree strongly	Mean	StDev	Median
Feedback on work was useful (Dept. level)	18.75%	43.75%	25.00%	12.50%	0.00%	3.69 (3.73)	0.95 (1.03)	4.00 (4.00)
	Much heavier	Somewhat heavier	Typical	Somewhat lighter	Much lighter	Mean	StD	Median
Workload for the course is (Dept. level)	6.25%	62.50%	25.00%	6.25%	0.00%	3.69 (3.71)	0.70 (0.98)	4.00 (4.00)