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COMMENTARY

# The Application of Engineering Principles and Practices to Medical Education: Preparing the Next Generation of Physicians

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## Introduction

Modern medicine is a dynamic, complex field that continually introduces new technology, seeks greater interconnectedness among disciplines, and faces increasing unpredictability about healthcare's future landscape. It is surprising, then, that the current scope of typical allopathic medical education continues to focus largely on inpatient clinical experience and thus is inadequate to the task of training future physicians to cope with dynamic, systemic changes in areas such as digital health, quality improvement, personalized medicine, regulations, and reimbursement models [1–4]. Historically, academic medical education sought to address these gaps in education through the creation of combined degree programs, such as the MD/PhD, MD/MPH, and MD/MBA; these programs allow medical students to pursue training in the non-clinical, yet crucial, aspects of medicine including research methods, population health, healthcare delivery, and healthcare management science [5–7]. Given the increasingly technological nature of healthcare changes, MD/MEng [8] programs are now beginning to gain traction because they help students acquire technical interdisciplinary skills that bridge the gap between clinical medicine and the increasingly demanding technological dimensions of the healthcare environment. The growing popularity of these engineering-focused combined degree programs indicates a pressing need for future clinical professionals to acquire skills and expertise beyond the traditional medical curriculum. We propose ways in which to incorporate fundamental aspects of engineering education to help medical students acquire these skills.

## Rationale

The decades-long expansion of biomedical device innovation and the dramatic recent growth of digital health have expanded the opportunities for the fields of engineering and medicine to find common ground over the past several decades. The traditional medical school curriculum has a primary focus on training physicians to diagnose medical conditions and manage treatment courses; however, it offers little to equip future physicians with the skills needed to assess the clinical relevance of novel medical devices, operational changes, or new approaches to providing treatments for patients with unmet medical needs [9]. As of 2017, there are approximately 190,000 engineering degrees awarded annually, with a yearly growth rate of nearly 6% [10]. Nevertheless, only approximately 1–2% of graduating engineers apply to medical school [11]. Data collected from the Association of American Medical Colleges (AAMC) shows that engineering majors comprise only 3–5% of applicants and matriculants alike (Tables 1 and 2) [12]. In contrast, applicants with majors such as Biological Sciences make up an overwhelming majority of medical school applicants and matriculants [11]. Thus, while engineers are well-prepared to offer effective solutions to medical problems, only a small percentage of engineering graduates matriculate to medical school.

## Why Engineering?

Engineering education is an interdisciplinary practice that emphasizes the application of scientific principles to find creative solutions to everyday problems that may have limited information available. Engineering requires both technical and inter-professional skills that blend creativity, collaboration, and experience with business acumen and entrepreneurship. An engineering education teaches students how to apply their knowledge and skills in a variety of occupations across many industry sectors [12]. Thus, the field of medicine stands to

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**Table 1** Raw data obtained from the AAMC showing the number of applicants to medical school with an engineering degree compared to the total number of applicants from the application cycles of years 2010–2011 to 2018–2019

| Year | Number of engineering applicants | Total number of applicants | Percentage of engineering applicants |
|---|---|---|---|
| 2010–2011 | 1856 | 42,741 | 4.34% |
| 2011–2012 | 1905 | 43,919 | 4.34% |
| 2012–2013 | 1969 | 45,266 | 4.35% |
| 2013–2014 | 2060 | 48,014 | 4.29% |
| 2014–2015 | 2042 | 49,480 | 4.13% |
| 2015–2016 | 2040 | 52,549 | 3.88% |
| 2016–2017 | 2035 | 53,042 | 3.84% |
| 2017–2018 | 1562 | 51,680 | 3.02% |
| 2018–2019 | 1931 | 52,777 | 3.66% |

gain significant benefits from the contributions of students with engineering backgrounds.

Engineers have well-honed quantitative and analytical skills to solve problems, understanding that solutions often require an iterative approach. Thus, engineers have the perspective, expertise, creativity, and pragmatism needed to successfully craft new systems, methods, and processes to adapt to medicine's highly dynamic environment. For example, three of the fourteen Grand Challenges for Engineering in the twenty-first century put forth by the National Academy of Engineering (NAE) involve healthcare [13]. These Grand Challenges were developed under the guidance of international technological experts to improve society through engineering. By including the theme of healthcare, the Grand Challenges exemplify the synergy that is needed between both fields. Specifically, these challenges are as follows: (1) to reverse engineer the brain, (2) to engineer better medicines, and (3) to advance health informatics.

In *The Engineer of 2020: Visions of Engineering in the New Century*, the NAE highlights key attributes of an engineer that are gained through appropriate education [14]. As shown in Table 3, these closely parallel the 15 core competencies for entering medical students set forth by the American Association of Medical Colleges (AAMC) [15]. The virtually complete overlap of these competencies points to the marked similarity of the fundamental skill sets that are needed in both the engineering sciences and medicine, which suggests that having a background in engineering could be helpful preparation for medical education. We highlight examples of how engineering training in problem-solving, innovation, systems-based thinking, collaboration, and interdisciplinary education can be translated to, and thus benefit, the field of medicine. We choose to highlight this subset of skills because they serve as a proxy for most of the core competencies listed in Table 3 and they provide the clearest examples of those aspects of engineering that are most applicable to medical education.

**Problem-Solving** Physicians require strong problem-solving skills. Engineering is one of the few undergraduate disciplines that explicitly focus on application-based, analytical problem-solving that offers important clinical reasoning skills for future physicians.

Problem-solving in the engineering realm is grounded in the "engineering design process." Though analogous to the hypothesis-driven experimental process, a key differentiating feature of the design process in engineering is the use of failures and unforeseen circumstances to adapt [16]. Although welcoming failure may seem counterintuitive to medicine, it, in fact, parallels medical practice. Medical students, residents,

**Table 2** Raw data obtained from the AAMC displaying the number of matriculants to medical school with an engineering degree compared to the total number of applicants from the application cycles of years 2010–2011 to 2018–2019

| Year | Number of engineering matriculants | Total number of matriculants | Percentage of engineering matriculants |
|---|---|---|---|
| 2010–2011 | 930 | 18,665 | 4.98% |
| 2011–2012 | 967 | 19,230 | 5.03% |
| 2012–2013 | 1036 | 19,517 | 5.31% |
| 2013–2014 | 1042 | 20,055 | 5.20% |
| 2014–2015 | 999 | 20,343 | 4.91% |
| 2015–2016 | 960 | 20,631 | 4.65% |
| 2016–2017 | 970 | 21,030 | 4.61% |
| 2017–2018 | 787 | 21,338 | 3.69% |
| 2018–2019 | 958 | 21,622 | 4.43% |

and practicing physicians alike are regularly faced with complex problems heavily weighted with either the potential for failure or the inability to solve a problem on the first try. For example, when the decision is made to treat a patient with depression with an antidepressant medication, treatment is usually initiated on a "trial and error" basis: a physician puts a patient on a "trial" of a certain antidepressant medication and adjusts dosing based on a patient's response to treatment; there is no "one size fits all" approach for treating all patients, even for those who present with similar symptoms [17]. Thus, clinicians must optimize solutions for their patients through a range of strategies: dose titration, addition of another drug, or transition to another treatment modality altogether. Closely linked, iterative thinking processes, another engineering trait, are therefore essential to medical practice, which become second nature through years of training.

**Innovation** Engineering training is likely to improve a physician's ability to understand the strengths and limitations of technologies that play an increasingly broader role in modern medicine. Likewise, a fundamental understanding of medical technology enables physicians to streamline patient care by redirecting their mental energies to patients themselves.

One approach to understanding technology and innovation is through design thinking and project-based learning, which are distinguishing features of an engineering education [18]. Design thinking is a method used to drive innovation and improve services in sectors such as healthcare [19]. Design thinking is often included as a capstone course in engineering education in which students translate an idea into a prototype. One of the initial steps of design thinking focuses on teaching students how to ask appropriate questions to define a problem that meets user criteria, given available resources. Other aspects of design thinking include considering system dynamics, reasoning about uncertainty, preparing estimates, and conducting experiments [18]. These aspects are directly transferable to the practice of clinical medicine when troubleshooting a broad range of issues, such as improving health outcomes, standardizing clinical processes, and reducing costs [20]. For example, during the early days of the COVID-19 pandemic, physicians were forced to create innovative solutions to help develop respirators and required personal protective equipment when faced with acute shortages of these items in the USA [21].

**Table 3** Comparison of the National Academy of Engineering key attributes with the 15 core competencies for entering medical students set forth by the AAMC

| NAE key attributes | AAMC core competencies |
|---|---|
| High ethical standards | Ethical responsibility to self and others |
| Strong analytical skills | Quantitative reasoning |
| | Critical thinking |
| | Scientific inquiry |
| | Living systems |
| Communication | Written communication |
| | Oral communication |
| Resilience<br>Flexibility | Resilience and adaptability |
| Agility | |
| Dynamism | |
| Leadership<br>Business and management | Teamwork |
| Professionalism | Reliability and dependability |
| | Cultural competence |
| | Social skills |
| | Human behavior |
| | Service orientation |
| Lifelong learners<br>Creativity | Capacity for improvement |
| Practical ingenuity | |

In another example, Dr. Herman Morchel, an emergency room physician at Hackensack Meridian Health, directly harnessed his engineering background to spearhead development of high-technology mobile emergency medical units, essentially intensive care units on wheels, as a way to extend critical care to where it was most needed while limiting spread of SARS-CoV-2 [22]. Such efforts, in addition to fostering an innovation-inclined mindset, greatly benefit from the design thinking process ingrained in engineering education.

Physicians with engineering backgrounds possess both clinical and technical skills that enable them to bridge the divide between engineering and medical disciplines to improve healthcare through technology. With the increasing popularity of technologies, including 3D printing, machine learning, and artificial intelligence, physicians with engineering backgrounds are uniquely positioned to contribute to medical education and biomedical research involving medicine, engineering, and technology. Additionally, since the implementation of new technologies in a medical setting is often quite challenging, physicians with engineering backgrounds are in the strategic position of being able to translate medical terminology into engineering jargon and vice versa, lessening the risk that valuable information will be lost in translation [9]. Furthermore, physicians with technical understanding are also able to facilitate physician buy-in regarding the integration of such new technology [23].

One clear example that shows how technology and innovation can come together in the healthcare setting is quality improvement (QI) initiatives. The expansion of these initiatives is due largely to the relatively recent requirements imposed by the US Accreditation Council for Graduate Medical Education (ACGME) that asks residency programs to provide QI education for medical trainees [24]. Individuals with backgrounds in design thinking, innovation, and technology are in an ideal position to identify and drive QI initiatives that occur at the rarefied intersections of technology with medicine, policy, and business.

**Systems-Based Thinking** The human body can be viewed as a complex physiological system. An engineering perspective facilitates understanding of systems-based thinking of the human body's physiological processes (e.g., modeling the cardiovascular system as an electrical circuit). Viewing these basic pre-clinical concepts through the lens of engineering can power the development of novel medicines and technologies.

Medical students are clearly expected to graduate with a competency in systems-level problem-solving abilities, according to the AAMC and the American Medical Association (AMA), but the means of attaining this competency and the degree to which it is integrated into students' medical education are less clear. One proven method of teaching this skill is inclusion of design thinking and innovation-related collaborative activities into medical education, as described above [1]. However, documentation of competence in the application to systems-level problem-solving will require further research.

**Collaboration** The importance of collaboration in medicine is well-established: it is widely accepted and appreciated that healthcare is a multidisciplinary field that requires close collaboration and communication among all of the different healthcare specialties and professions to deliver high-quality patient care. Additionally, medicine is a rapidly changing field that demands timely adaptability on the part of both the individual and the team. Thus, cross-functional communication is critical as patient cases are infrequently simple and uncommonly isolated to one profession or even one specialty. Finally, collaborative learning goes beyond simple crosstalk and seeks to instill values of shared goals, teamwork, trust, continual learning, individual responsibility, and self-discipline [25].

While most medical schools recognize the need for students to develop collaborative skills, attempts at teaching best practices are often overshadowed by the rigor and competitiveness of other required course material. Notably, for undergraduate students in the USA, pre-medical education encompasses the "formal curriculum as well as informal and hidden curricula"; collaborative learning remains largely a part of the hidden curriculum [26]. While certain pre-medical courses, such as biology and chemistry, may involve collaboration, such as having a partner for laboratory exercises, the emphasis is still placed on the individual and not on collaboration or teamwork. In fact, pre-medical curricular requirements generally include "weeder" courses that, to the contrary, emphasize competition among students based on exams, individual assignments, and letter grades [26]. Even those who seek additional opportunities, such as research or volunteer work, have no assurance that they will be exposed to team-based learning or collaboration, since these endeavors may be pursued in isolation, for example, under a fume hood or behind a desk. Once these students reach medical school, they may find it challenging or even uncomfortable to develop adequate flexibility in assuming roles and responsibilities in different team environments while they ascend the generally lock-stepped medical hierarchy as medical students, residents, fellows, and attending physicians.

Weak collaboration skills can also have detrimental effects on the students themselves: by choosing individual approaches to work habits over collaborative approaches for the sake of comfort, they could isolate themselves from potential peer support systems that are crucial to the development of resilience and success in medical school. It could be argued that, given the lack of insight needed to seek support from classmates, the under-emphasis of collaborative skills during pre-medical education may actually accelerate early withdrawal of students from the pre-medical track [26]. Furthermore, collaboration may be key to combating physician burnout and the resulting shortage of healthcare professionals in the USA.

In contrast, the cornerstone of the engineering field is an emphasis on collaboration: Engineers recognize that a complex problem is rarely solved by an individual. Instead, a team effort is required to produce a solution to a complex problem. While all engineering students must participate in a core curriculum of lower division courses that may be individually focused and initially exam-based, most upper division courses require extensive amounts of group work and collaboration [27]. This requirement leads to a learning environment that encourages students to efficiently resolve challenges arising from interpersonal conflict and to quickly adapt to changing roles throughout their educational journey.

While efforts at the medical school level to increase collaboration through small group sessions and problem-based learning are laudable, looking to the model of engineering education may help to solidify such skills earlier in the overall educational process and accomplish the task in more robust way.

**Interdisciplinary Education** There is indirect evidence for medical school recognition of the importance of an engineering background. AAMC data from the application cycles of 2010–2011 to 2018–2019 show the matriculation rate for engineering majors is consistently greater (6.44–9.50%) than the average overall matriculation rate for applicants (Table 4) [11]. This finding suggests that students who complete engineering curricula are better positioned for admission to medical school than the general, non-engineering trained applicant, based on the attributes highlighted above.

**Table 4** Raw data from AAMC comparing the overall (general) matriculation rate of medical school applicants compared to the matriculation rate of those applying with engineering degrees from the application cycles of years 2010–2011 to 2018–2019

| Year | General matriculation rate | Engineering matriculation rate | Difference |
|---|---|---|---|
| 2010–2011 | 43.67% | 50.11% | 6.44% |
| 2011–2012 | 43.79% | 50.76% | 6.98% |
| 2012–2013 | 43.12% | 52.62% | 9.50% |
| 2013–2014 | 41.77% | 50.58% | 8.81% |
| 2014–2015 | 41.11% | 48.92% | 7.81% |
| 2015–2016 | 39.26% | 47.06% | 7.80% |
| 2016–2017 | 39.65% | 47.67% | 8.02% |
| 2017–2018 | 41.29% | 50.38% | 9.10% |
| 2018–2019 | 40.97% | 49.61% | 8.64% |

In a similar manner, there is an evident trend in interdisciplinary medical curricula related to engineering. The Carle Illinois School of Medicine, discussed below, is the first engineering-based medical school to focus on furthering improvement and innovation of patient care in this manner [28]. This trend is not a novel concept. For example, Dr. René Favaloro (July 12, 1923–July 29, 2000), a cardiovascular surgeon well-known for his contributions to the standardization of coronary artery bypass surgery, felt strongly that "individualism had to be replaced by collective interests… through daily preventive education" and that "projects are more important than disciplines" [29]. Thus, a new, interdisciplinary curriculum is proposed that integrates engineering with biological sciences to inform functional interoperability, exchanges rote memorization for applied knowledge, and sparks creativity [29]. This type of integrated curriculum could alter the relationship between medical education and biomedical research by encouraging physician-scientists to couple biomedical research with engineering and technology. As another example, select MD/PhD programs have established partnerships with engineering schools to take advantage of the intersection of their highly specialized knowledge and skills with rapidly advancing fields of medical technology [30].

The combination of engineering and medicine holds the potential to empower future clinicians to make an impact not only in medicine but also in the larger healthcare sector by leveraging the expertise needed to be at the forefront of healthcare innovation, entrepreneurship, and research [8]. Thus, the integration of engineering-related concepts into medical education should become more widespread.

**Schools and Programs That Combine Engineering and Medicine** The Carle Illinois College of Medicine, created in partnership by the University of Illinois at Urbana-Champaign and the Carle Health System, is the first medical school in the world to incorporate engineering principles into the traditional medical school curriculum. Instead of compartmentalizing medicine and engineering, Carle synthesizes the fields of biological science, clinical applications, and engineering by course [28].

While not as integrated as Carle, other academic institutions also see the benefits of combining engineering training and medical education to tackle the complexity of modern medicine. By offering courses such as "Matlab for Medicine," Harvard's Health Sciences and Technology program, a collaboration with the Massachusetts Institute of Technology, encourages medical students to engage in interdisciplinary research, "bring clinical insights from the bedside to the bench," and vice versa [31]. This program also requires student applicants to "be comfortable with mathematics and computational methods," skills also required of engineering students [32]. The Health, Technology, and Engineering program at the University of Southern California (HTE@USC) brings together medical and engineering students through case-based instruction and project-based collaboration to identify and solve real-world healthcare problems [33]. As evidenced by these examples, there is growing appreciation of the fact that bench-to-bedside research is rarely a straightforward collaborative enterprise and that there may be a misalignment among the participants. For example, academia is often satisfied with publications and grants, but healthcare entrepreneurship requires further demonstration of proof of concept and implementation [34].

## How Can We Implement These Ideas?

In our present and increasingly competitive drive for talent, medical schools and graduate medical education programs could benefit from updated programmatic approaches that specifically bridge the fields of engineering and medicine. The following recommendations discuss focused diversification of the student body through inclusion of engineering majors [1, 2]; improvements in the medical curriculum through addition of engineering principles and collaborative work styles [3–5]; and structural measures to sustain programmatic changes through the establishment of new interdisciplinary societies and cross-disciplinary journals [6]. While the focus of these recommendations is best considered at the institutional level, that is, the Liaison Committee on Medical Education (LCME) and the ACGME, other stakeholders in medical education are welcomed to assist with their implementation:

1. That medical schools develop policies and procedures that have greater flexibility with admissions requirements for non-traditional applicants. Barriers such as admissions committees' negative perceptions of lower GPAs in engineering majors due to increased course units and academic rigor can prevent acceptance of engineering students into medical school programs. Flexibility with such requirements may increase applicant number and diversity and encourage prospective pre-medical students to pursue engineering majors. Additionally, an emphasis on the demonstration of collaborative activities through coursework or extra-curricular activities may facilitate earlier development of relevant skills that can then be honed in a healthcare context.
2. That medical schools actively seek students with diverse educational backgrounds with experiences in an interdisciplinary field, such as engineering, the humanities, or social sciences. Such experiences are likely to enhance skills needed in medicine, such as adaptability and tolerance of ambiguity, and contribute to the diversity of medical professionals.
3. That medical schools seek opportunities to integrate engineering principles and practices into the medical education curriculum. For example, a brief electrophysiology course in basic circuitry may better equip students to understand conductance and resistance related to the nervous and cardiovascular systems. Additionally, incorporation of a course in design thinking would increase capabilities in problem-solving, resilience, collaboration, innovation, and creativity. Inviting guest speakers such as engineers working on medically relevant projects may further contribute to and reinforce integration of engineering and medicine.
4. That medical schools augment their curricula with early collaborative experiences to teach students how to seek support, thus inculcating habits that can foster lifelong resilience and success. Though exams are necessary preparation for standardized tests and individual responsibility, a greater proportion of team projects may overcome the hallmark rigors of medical school stemming from isolation and individual work.
5. That graduate medical education programs incorporate engineering principles during training for residencies and fellowships in technologically heavy specialties such as radiology [35]. Emphasis on working with other medical professionals and offering master's degrees in engineering disciplines may facilitate the development of innovative approaches to medical problems.
6. That the medical profession establishes interdisciplinary societies and cross-disciplinary journals that emphasize careers in physician entrepreneurship and innovation. By harnessing problem-solving, systems-based thinking, collaboration, and interdisciplinary attitudes, these programs would encourage physicians to be at the forefront of medical innovation and technological implementation in the healthcare field.

It is imperative to track the effects of the aforementioned recommendations to understand their impact on medical students and medical education. Continuing to track the proportions of engineers in the applicant, matriculant, and graduate pools across medical schools will help us understand whether these changes have attracted more engineers to the field of medicine. Regarding academic and curriculum changes, serial assessments and surveys of students can provide further insight into ways that will continue to enhance medical education. For example, student grades and board scores can be tracked for performance outcomes as engineering principles are implemented in curricula. Additionally, students could be asked explicitly through surveys whether the incorporation of engineering principles facilitated better conceptual understanding and retention of key concepts after taking relevant board or certification exams. Similarly, after group projects, students may be surveyed about their experience and how they felt about working in a team. As students progress into clinical rotations and residencies, longitudinal surveys and evaluations incorporating clerkship directors and program directors can be used to track trainees' willingness and adaptability to collaborate. These surveys could also be done within or across specialties. Innovation metrics can be tracked at different programs and institutions through numbers of intellectual property filings, joint ventures, publications, and general garnered interest in clubs and activities focused on technological advances. Finally, these changes, such as replacing individual exams with more group evaluations, may improve student well-being and mental health, and may ultimately be a factor in addressing physician burnout. Since we believe these recommendations will have a long-term impact on an individual student's medical career, all outcomes can be tracked longitudinally to verify these hypotheses and help inform medical education practices.

## Conclusion

Solving the challenges of a rapidly changing healthcare system requires training and expertise beyond the basic and clinical sciences of traditional medical education. We propose that greater inclusion of engineers into the ranks of healthcare providers, introduction of engineering principles and practices to medical education, and incorporation of the social skills crucial to both engineering and medicine are all necessary to drive the evolution of medical education.

## Compliance with Ethical Standards

**Conflict of Interest** MR, AB, and HK report no conflicts of interest. PB was employed by Sanofi until his retirement in April, 2017. He has been a guest speaker at commercial venues, Proventa in 2018 and Veeva in 2019, that provided transportation and hotel accommodations, and he has been a consultant to pharmaceutical companies for less than 5% of his professional time.

**Ethical Approval** Reported as not applicable

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## References

1. Niccum BA, Sarker A, Wolf SJ, Trowbridge MJ. Innovation and entrepreneurship programs in US medical education: a landscape review and thematic analysis. Med Educ Online. 2017;22(1):1360722. https://doi.org/10.1080/10872981.2017.1360722.
2. Han ER, Yeo S, Kim MJ, Lee YH, Park KH, Roh H. Medical education trends for future physicians in the era of advanced technology and artificial intelligence: an integrative review. BMC Med Educ. 2019;19:460 (2019). https://doi.org/10.1186/s12909-019-1891-5.
3. Nyquist JG. Educating physicians: a call for reform of medical school and residency. J Chiropr Educ. 2011;25(2):193–5.
4. Irby D, Cooke M, O Brien B. Calls for reform of medical education by the Carnegie Foundation for the Advancement of Teaching: 1910 and 2010. Acad Med. 2010;85(2):220–7.
5. Considering a combined degree: MD-PhD, MD-MBA, MD-MPH, MD-JD. (2018, October 03). https://students-residents.aamc.org/applying-medical-school/article/considering-combined-degree-md-phd-md-mba-md-mph/. Accessed December 24, 2020.
6. Viswanathan, V. (2014). The rise of the M.D./M.B.A. Degree. https://www.theatlantic.com/education/archive/2014/09/the-rise-of-the-mdmba-degree/380683/. Accessed December 24, 2020.
7. Kossoff, L. (2019). Why more MDs, Medical residents are choosing to pursue additional academic degrees - ENTtoday. https://www.enttoday.org/article/why-more-mds-medical-residents-are-choosing-to-pursue-additional-academic-degrees/?singlepage=1&theme=print-friendly . Accessed December 24, 2020.
8. MD-Master of Engineering Dual Degree. (2019, October 29). https://bme.duke.edu/grad/masters/md-meng. Accessed December 24, 2020.
9. Pierce, S., & Becker, A. (2019). Physician-engineers poised to transform health care. https://www.tmc.edu/news/2019/04/physician-engineers-poised-to-transform-health-care/. Accessed December 24, 2020.
10. Deloitte. (n.d.). Engineering. https://datausa.io/profile/cip/engineering. Accessed December 24, 2020.
11. AMCAS. (2020). [Annual breakdown of AMCAS applicants, matriculants and graduates in US medical schools]. Unpublished raw data.
12. Understanding the educational and career pathways of engineers. National Academy of Engineering; 2018. https://doi.org/10.17226/25284. Accessed December 24, 2020.
13. 14 Grand Challenges for Engineering. (2018). http://www.engineeringchallenges.org/challenges.aspx. Accessed December 24, 2020.
14. The engineer of 2020: visions of engineering in the new century. (2004). National Academy of Engineering. https://doi.org/10.17226/10999
15. AAMC. (n.d.). The core competencies for entering medical students. https://students-residents.aamc.org/applying-medical-school/article/core-competencies/. Accessed December 24, 2020.
16. University of North Carolina Wilmington. (n.d.). What is engineering? Engineering expectations. https://uncw.edu/engineeringexpectations/documents/general/whatisengineering.pdf. Accessed December 24, 2020.
17. Nichols, H. (2018). Why antidepressants fail to work in some people. https://www.medicalnewstoday.com/articles/320506.php. Accessed December 24, 2020.
18. Dynn C, Agogino A, Eris O, Frey D, Leifer L. Engineering design thinking, teaching, and learning. IEEE Eng Manag Rev. 2006;34(1):65. https://doi.org/10.1109/emr.2006.1679078.
19. Ku, B., Shah, A., & Rosen, P. (2016). Making design thinking a part of medical education. https://catalyst.nejm.org/making-design-thinking-part-medical-education/. Accessed December 24, 2020.
20. Beninger P, Li D, Baaj A. Entrepreneurship for a meaningful clinical experience. BMJ Innov. 2019;5(1):1–7. https://doi.org/10.1136/bmjinnov-2018-000295.
21. Kim, H., Demehri, F., Crum, R., Slatnick, B., Wu, K., & Yu, L. (2020). Surgical innovation fellowship: COVID-19: our response to the N95 shortage. http://www.childrenshospital.org/research/departments-divisions-programs/departments/surgery/surgical-innovation-fellowship. Accessed December 24, 2020.
22. Stevens Institute of Technology (2020). During COVID-19, physician's unique talents and perspective make all the difference 23. www.stevens.edu/news/during-covid-19-physicians-unique-talents-and-perspective-make-all-difference. Accessed December 27, 2020.
23. Klaassen, J. (2018). Forming the link between physician and engineer. https://www.physiciansweekly.com/forming-the-link-between-physician-and-engineer/. Accessed December 24, 2020.
24. Accreditation Council for Graduate Medical Education (ACGME). (n.d.). Common program requirement. http://www.acgme.org/What-We-Do/Accreditation/Common-Program-Requirements. Accessed December 24, 2020.
25. Göl, Ö., & Nafalski, A. (2007). Collaborative learning in engineering education. Global J. of Engng. Educ., 11(2), 173–180. http://www.wiete.com.au/journals/GJEE/Publish/Vol.11,No.2/GolNafalski.pdf. Accessed December 24, 2020.
26. Lin KY, Parnami S, Fuhrel-Forbis A, Anspach RR, Crawford B, Vries RG. The undergraduate premedical experience in the United States: a critical review. Int J Med Educ. 2013;4:26–37. https://doi.org/10.5116/ijme.5103.a8d3.
27. Schmidt LC. Engineering teams: individual or group sport? Int J Engng Ed. 2006;22(3):659–64.
28. Strickland E. (2018). Tomorrow's doctors must be engineers too. https://spectrum.ieee.org/at-work/education/tomorrows-doctors-must-be-engineers-too. Accessed December 24, 2020.
29. Armentano, RL et al. (2004). A proposal to enhance engineering education in biology and medicine by following the legacy of René Favaloro. IEEE Service Center, Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society (pp. 3977-3980).
30. National Institute of General Medical Sciences. (n.d.). Medical scientist training program. https://www.nigms.nih.gov/training/instpredoc/pages/predocoverview-mstp.aspx. Accessed December 24, 2020.

31. Harvard Medical School. (n.d.). Health sciences & technology. https://meded.hms.harvard.edu/health-sciences-technology. Accessed December 24, 2020.
32. Applying to the HST MD program. (n.d.). https://hst.mit.edu/applying-hst/applying-hst-md-program. Accessed December 24, 2020.
33. USC. (n.d.). Health, technology, and engineering. https://hte.usc.edu/about/. Accessed December 24, 2020.
34. Spertus JA. Leveraging entrepreneurship as a means to improve the translation of outcomes research to healthcare improvement. Circulation. 2015;8(1):2–3. https://doi.org/10.1161/circoutcomes.114.001641.
35. Samei E, Grist TM. Why physics in medicine? JACR. 2018;15(7):1008–12. https://doi.org/10.1016/j.jacr.2018.03.043.