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Radiology Education For U.s. Medical Students In 2024: A State-Of-The-Art Analysis

Ryan Bahar

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Radiology Education for U.S. Medical Students in 2024: A State-of-the-Art Analysis

A Thesis Submitted to the Yale University School of Medicine in Partial Fulfillment of
the Requirements for the Degree of Doctor of Medicine

by
Ryan Cameron Bahar
2024
RADIOLOGY EDUCATION FOR U.S. MEDICAL STUDENTS IN 2024: A STATE-OF-THE-ART ANALYSIS

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Radiology is essential to the practice of clinical medicine, with ever-increasing volumes of diagnostic imaging studies and image-guided procedures across the U.S. healthcare system. Yet, radiology education has received criticism for its under-representation in formal U.S. medical school curricula, coupled with variable requirements and offerings among institutions. Recent national calls for medical education reform (e.g., the 2010 Carnegie report) and the emergence of new teaching tools (e.g., e-learning, simulation) have led to paradigm shifts in medical education delivery that have been further accelerated by the unprecedented alterations to educational environments catalyzed by the COVID-19 pandemic. In this landscape of profound change, numerous works have reported on curricular restructuring and innovations in radiology, extracurricular radiology educational activities, and trainee and faculty perceptions of radiology education, among other domains, at both institutional and national scales. However, there is a paucity of literature synthesizing these reports into a coherent and comprehensive illustration of the current status of radiology in American undergraduate medical education. This thesis aims to provide a state-of-the-art review of contemporary radiology education for U.S. medical students by contextualizing its historical underpinnings, highlighting key themes and trends in radiology educational practice, and anticipating future directions for continued paradigmatic evolution.
This thesis follows the six-stage approach for conducting a state-of-the-art review as described in the literature. A comprehensive search was performed between September and December 2023 using five online databases: OVID Medline, Embase, ERIC, PsycInfo, and PubMed. Search strategies were developed in collaboration with an institutional librarian. Additional literature was obtained through manual exploration of article citations and education-tagged articles on radiology journal websites.

280 relevant articles were identified in the search. Subsequent thematic analysis revealed eight major trends in medical student radiology education: (1) integration of radiology into earlier phases of medical school curricula, with most schools not requiring a distinct preclinical or clinical course experience in radiology; (2) transformation of radiology clerkship and elective activities into more active, self-directed learning experiences; (3) heightened curricular emphasis on non-interpretive imaging skills; (4) incorporation of standardized radiology curricula into institutional educational activities; (5) shift to virtual radiology clerkship and elective activities during the COVID pandemic, with persistence into the post-pandemic era; (6) emergence of digital and microlearning tools supplementing formal education; (7) creation of extracurricular radiology experiential learning opportunities; and (8) discussions of radiology trainee diversity and imaging care disparities.

Medical student radiology education has changed significantly in the 21st century. Understanding this shift is crucial for maintaining and reshaping medical student radiology education to meet the needs of an ever-evolving profession and society.
ACKNOWLEDGEMENTS

Fundamentally, this thesis is a celebration of educational achievements borne from the innovative minds and tireless, loving work of educators. It is only befitting to acknowledge the educators who have shaped me over the years—from the Georgetown Public Schools System, to Brown University, all the way to Klvaňovo Gymnázium a Střední Zdravotnická Škola in Kyjov, Czech Republic, and now at the Yale School of Medicine—without whom this thesis (or my existence, as I know it) would not have been possible. In the village of names whom have forever earned my gratitude, I would especially like to thank Dr. Janet Hafler and Dr. Jeremy Moeller for encouraging my educator pursuits, and in particular, honing my ambition for educational scholarship from the first year of medical school; Dr. Mariam Aboian for the effervescently kind mentorship that drew me into radiology and for role-modelling collaboration and resilience in research; and Dr. Thilan Wijesekera for empowering me to marry my clinical and educational interests through curriculum development, inspiring me to pursue this thesis, and patiently and graciously guiding me through the finish line. Regarding this thesis, I would like to extend my utmost appreciation to Dr. Judy Spak for streamlining the literature search upholding through work by generously sharing her expertise and resources.

To my family (Mary, Mory, Nina), my partner (Noah), and my friends, this thesis is just as much yours as it is mine. Thank you for unconditionally investing your lives into my well-being and success; there is no greater act of love.
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INTRODUCTION

The use of imaging to guide diagnosis, surveillance, and treatment has become an instrumental component of patient care in the United States. Imaging volumes and image-guided procedures reached an all-time high before the COVID-19 pandemic and are projected to continue to increase (Hornbrook et al. 2012, Poyiadji et al. 2023). Moreover, nearly all clinical specialties utilize imaging and depend on radiologists. As radiologists have discussed in the literature, medical student education in radiology is essential to prepare future clinicians—radiologists and non-radiologists alike—with the understanding of the role of radiology in daily clinical practice (Farmakis et al. 2023, Miller et al. 2023, Oancea et al. 2013). Yet, radiology education is criticized for its under-representation in formal U.S. medical school curricula, with trainees and faculty across specialties calling for more medical student radiology training over the years (du Cret et al. 1994, Collins et al. 2002, Farmakis et al. 2023, Poot et al. 2012, Rangaswamy et al. 2023, Rohren et al. 2022, Straus et al. 2014).

Radiology and Medical Education: A Brief History

To conceptualize the current state of undergraduate medical education (UME) radiology curricula, the histories of radiology and medical education—as well as their intersection—are crucial to grasp. After Wilhelm Roentgen discovered x-rays in 1895—the first year that the inside of the human body was able to be imaged—the scientific community exploded with research on the subject, publishing 1,044 articles over the following year (Thomas &
Banerjee 2013). Radiographs became fundamental to clinical diagnosis in the ensuing decades, with military use of x-rays for assessing injuries documented as early as World War I (Hessenbruch 2002, Scatliff 2014). Fluoroscopy also emerged as an important diagnostic imaging modality (Levine & Rubesin 2017). Coincidentally, modern American medical education was originating at this time following the publication of the 1910 Flexner Report (Duffy 2011). Deriving inspiration from the contemporary model for German medical education, The Flexner Report reformed medical education to eliminate proprietary schools and center biomedical science in medical training, with basic sciences in the first two years and clinical sciences in the last two years. Radiographs and fluoroscopy were a nascent technology at this time of critical transformation in medical education. Nevertheless, radiology curricula in UME have been evident in the literature since the early 1900s (Linaker 2015). In 1927, Bardeen reported using radiography and fluoroscopy to teach anatomy to students at the Medical School of Marquette University (Bardeen 1927). For decades after, these modalities monopolized medical imaging, until eventually three-dimensional imaging, functional imaging, and molecular imaging techniques acquired significant presence. More than 50 years after the Flexner Report transformed American medical education, ultrasound became a routine form of diagnostic imaging in the 1970s. The computer tomography (CT) scanner was invented in 1967, with the first patient scan occurring in 1971. Magnetic resonance imaging (MRI) emerged in the 1970s (Viard et al. 2021). Over the subsequent decades, access to advanced imaging rapidly progressed: between 1993 and 2021 the number of MRI scanners per million inhabitants in the United States nearly quadrupled (OECD 2024). In parallel with the growth of clinical imaging techniques,
medical education continued to evolve. In 1942, the Association of American Medical Colleges (AAMC) formed The Liaison Committee on Medical Education (LCME) as the accrediting agency of U.S. medical programs. The LCME was designed to protect trainees from the WWII draft and maintain medical education quality (Kasselbaum 1992). It evolved to ensure standards for education that enforced consistency in training among medical schools. However, radiology had minimal incorporation into LCME accreditation standards, and most U.S. medical schools did not have required imaging courses or rotations (Barlev et al. 1994). Around the turn of the 21st century, the medical educators in radiology joined together to create the American Medical Student Educators in Radiology, an organization whose mission, in part, is to “promote radiology as an essential component of the medical school curriculum (Association of University Radiologists 2024, Samuel and Shaffer 2000). At the time, radiology was facing dramatic changes with film, analog images, and paper reports being replaced by monitors, digital images, and electronic communications (Buchmann and Greenberg 2009). Online teaching files and other Web-based learning tools burgeoned. Evolving medical school curricula and technological changes afforded radiologists greater opportunity to teach anatomy to medical students and participate in pre-clinical education (Samuel and Shaffer 2000), while the low prevalence of radiology clerkships began to further decline. A 1994 survey found 32% of American medical schools to have radiology clerkships (Barlev et al. 1994). Six years later, only 29% of American medical schools required them (Samuel and Shaffer 2000), and in 2009-2010, AAMC data showed that slightly less (25%) required radiology as a clinical rotation (Poot et al. 2012). By 2014, contemporary surveys showed that only 10-25% of medical school graduates had
required radiology rotations (Straus et al. 2014). Lee et al. reported in 2020 that approximately 20% of U.S. medical schools required radiology rotations, a stable percentage between 2011 and 2018 (Lee et al. 2020). In the 2019-2020 LCME Annual Medical School Questionnaire Part II Data, 16% of medical schools required radiology clerkships, down from 24% in 2014-2015 (Association of American Medical Colleges 2024). The decrease in standalone radiology clerkships came as more medical students began to integrate radiology into other courses (Association of American Medical Colleges 2024).

Diagnostic imaging innovations did not arise in isolation. Interventional radiology (IR), a field dedicated to minimally-invasive image-guided procedures, arose in the 1960s, though its origins in angiography began in 1923 (Bercovich and Javitt, 2018). From the advent of the Seldinger technique for achieving vascular access percutaneously in 1953, to percutaneous angioplasty in 1969, to percutaneous gallstone extraction in 1972, to endovascular stenting in 1973, to balloon-expandable stents for transjugular intrahepatic portosystemic shunts in 1986, the field has continued to evolve vascular and non-vascular techniques (Kellett et al. 1988, Tang et al. 2014). Vascular and interventional radiology officially became recognized as a subspecialty of diagnostic radiology in 1994 (Marx 2017), and in 2012, the American Board of Medical Specialties approved a certificate in interventional radiology that enabled its recognition as a primary specialty (Recht 2016). This prompted the creation of the IR integrated residency in 2014 (Marx 2017), which in turn bolstered opportunities for medical students to pursue IR rotations in U.S. medical schools (Goldman et al. 2018). Previously, medical students looking to explore IR were
generally limited to brief experiences on the service during diagnostic radiology or surgery rotations.

*Existing Reports of the State of Radiology in Undergraduate Medical Education*

Prior to the 21st century, published works in radiology education were sparse (Collins et al. 2001). With the body of literature growing, several works have reported on the state of radiology in undergraduate medical education (Barlev et al. 1994, Goldman et al. 2018, Lee et al. 2020, Linaker 2015, Oancea et al. 2013, Poot et al. 2012, Rohren et al. 2022, Rubin & Blackham 2015, Samuel & Shaffer 2000, Straus et al. 2014). In collection, these works reflect extensive surveying—both of medical students and radiology educational leaders—data-gathering, and literature searching to evaluate radiology curriculum in U.S. medical schools (Table 1).

In a 2020 survey of 472 medical students across 31 medical schools, Rohren et al. found that didactic lectures were the most common radiologic teaching method, radiologists were preclinical students’ primary radiology instructors, a majority of students had not heard of the American College of Radiology (ACR) appropriateness criteria, and nearly three-quarters of students believed they received too little radiology education (Rohren et al. 2022). Lee et al., analyzing AAMC Curricular Reports, reported that the duration of required radiology rotations to increase significantly from 2011 to 2018 yet the number of U.S. medical schools requiring them to be relatively unchanged at 20%, as described previously (Lee et al. 2020). Focusing on interventional radiology education, Goldman et al. searched school websites and course listings for clerkship availability and concluded
that 71% have dedicated IR rotations, with only 8% categorized as sub-internships (Goldman et al. 2018). Rubin and Blackman surveyed directors of anatomy and/or radiology courses for information about preclinical radiology teaching, uncovering that curricula are nonstandard, integrated, and primarily designed for anatomy correlation (Rubin and Blackman, 2015). Linaker performed a literature search of undergraduate radiology curricula globally through 2012 on five databases, and identified several areas of focus: what curricula should entail, when it should be taught, how it should be incorporated (integrated, independent, or both), and barriers to incorporation (limited undergraduate curricular hours, faculty time constraints, poor teaching remuneration, and non-radiologist instruction) (Linaker 2015). In their American College of Radiology (ACR)/Alliance of Medical School Educators in Radiology (AMSER) white paper on medical imaging education, Straus et al. surveyed U.S. allopathic radiology chairs and medical school deans, reporting that the majority believe more medical imaging instruction is needed across all four years of medical school and radiologists should be involved with medical imaging education (Straus et al. 2014). While leaders of radiologic instruction were most commonly non-radiologists, the vast majority of radiology department chairs indicated that non-radiologists could not adequately teach medical imaging.

In a recent perspective piece, Farmakis et al. summarized this current state concisely:

“...education requirements in U.S. medical schools are variable with only a minority of schools requiring a clerkship in radiology. When required, the radiology curriculum is often limited to anatomy courses in the preclinical years or partially incorporated into required core clerkships and often taught by nonradiologists” (Farmakis et al. 2023).
Eight years earlier, Linaker agreed with this limited presence of formal radiology education in medical schools and further concluded in her literature review:

“The remaining literature on radiology education curricula consists of debates and suggestions for curricular content, descriptions of existing programs, and proposals for methods incorporating radiology into various programs…No agreement exists in these areas” (Linaker 2015).
Table 1: Themes of Existing Reports on the State of U.S. Medical Student Radiology Education. “X” indicates the theme is present, and “-” indicates the theme is absent. A = active learning. B = digital and microlearning tools. C = trainee diversity and health equity. D = extracurricular learning experiences. E = curricular integration and early

From this group of studies reporting on the state of radiology education in medical schools, several gaps in topical understanding emerge:

1. As Linaker discusses, descriptions of existing programs are abundant in the literature. While they may not necessarily “agree” with one another, can study of these reports illuminate broader, significant trends in undergraduate radiology medical education that point to evolution of the field?

2. Given these studies do not include data past early-mid 2020, how has the COVID-19 pandemic affected undergraduate radiology medical education?

3. What salient aspects of radiology education—e.g., learning experiences outside of the classroom, development of nationally standardized curricula, proliferation of digital and social media-based learning—ought to receive further attention than these studies have captured (or wholly omitted)?

*Rationale of Present Study*

Recent national calls for medical education reform (e.g., the 2010 Carnegie report) and the emergence of new teaching tools (e.g., e-learning, simulation) have led to paradigm shifts in medical education delivery that have been further accelerated by the unprecedented alterations to educational environments catalyzed by the COVID-19
pandemic (Irby et al. 2010, Walters et al. 2022). In this landscape of recent and profound change, numerous individual works have reported on radiology curricular restructuring and innovations, extracurricular radiology educational activities, and diversity and health equity in radiology, among other domains, at both institutional and national scales. However, there is a paucity of contemporary literature synthesizing these reports into a coherent and comprehensive illustration of the current state of radiology in American undergraduate medical education. Moreover, existing literature contains the gaps described above.

**Contribution to Medicine**

This study aims to assess the current state of radiology education for U.S. medical students. Assessment will enable radiology educators to better understand shortcomings in medical student education—institutionally and nationally—as well as recognize suitable tools and curricular ideas to implement and overcome these shortcomings. Through the highlighting of key trends, radiology educators can learn about cutting-edge happenings in their field and continue the discussion. As education is essential to the provision of superlative health care, this work, in the broadest of strokes, aspires to better patient and population health.
STATEMENT OF PURPOSE

The purpose of this thesis is to perform a state-of-the-art review of the literature concerning radiology education for medical students in the United States. Specific objectives include:

a. To analyze key themes and trends in contemporary radiology undergraduate medical educational practice, with special attention to:
   i. Topics underrepresented in the body of literature reporting on the state of radiology education, including:
      1. Standardization of curricula
      2. Extracurricular learning experiences
      3. Digital and microlearning tools
      4. Pandemic and post-pandemic changes in education delivery
      5. Trainee diversity and health equity
   ii. Topics reported in the literature that could benefit from further study and synthesis:
      1. Curricular integration and earlier radiology exposure
      2. Active learning approaches on rotations
      3. Teaching non-interpretive skills
b. To explore directions for further evolution of the radiology undergraduate medical education paradigm
METHODS

Student Contributions

Ryan Bahar (R.B.) conceptualized initial questions and aims of this work with help from my thesis advisor, Dr. Thilan Wijesekera (T.W.). Dr. Judy Spak (J.S.), Head of Academic Research and Education at the Cushing/Whitney Medical Library, provided resources about various review types and refined the approach of this review to be state-of-the-art. She also provided a template search hedge that R.B. adapted to create a final search hedge for database query after consulting with her, and she suggested the names of the five databases searched in this study. R.B executed the database search, identification of relevant literature from search results, full-text review, literature interpretation and analysis, and qualitative thematic assessment with T.W.’s advising. R.B. wrote the original draft of this thesis, which T.W. reviewed and provided helpful suggestions and edits that R.B. incorporated into the final product.

Ethics Statement

The authors have no conflicts of interests to declare. No sources of funding are associated with this study. Institutional review board approval and informed consent was not necessary in the absence of research subjects.
Methods Description

This thesis follows the six-stage approach for conducting a state-of-the-art review as described below (Barry et al. 2022, Barry et al. 2022, Barry et al. 2022). State-of-the-art reviews commonly address current approaches, with less attention to retrospective matters, and may offer novel perspectives and identify areas of further research (Grant and Booth 2009).

Stage one: determine initial research question and field of inquiry

The initial research question was developed in September 2023 and can be summarized as: what is the current state of established radiology curricula in U.S. medical schools, non-radiology residency programs, and radiology residencies?

Stage two: determine timeframe

The timeframe for the state-of-the-art analysis was designated as 2014-2023. Several reasons underlie this choice of timeframe. First, the most recent ten-year period enables the review to be contemporary yet substantive given the high number of articles published during this period. Second, the window includes multiple years of radiology education reporting prior to the pandemic and thereafter. Third, 2014 is the year that the Accreditation Council for Graduate Medical Education (ACGME) approved a separate interventional radiology residency (Marx 2017), irreversibly renegotiating the landscape
of radiology education, and a state-of-the-art review beginning the year of this milestone could underscore subsequent changes. Fourth, in 2014, the American College of Radiology (ACR)/Alliance of Medical School Educators in Radiology (AMSER) white paper specifically called for reform to radiology education (Straus et al. 2014). Fifth, this timeframe falls after the data collection period of most other works reporting on the state of radiology education (Barlev et al. 1994, Linaker 2015, Oancea et al. 2013, Poot et al. 2012, Rubin and Blackham 2015, Samuel and Shaffer 2000, Webb et al. 2015).

Stage three: finalize research question(s) to reflect timeframe

A birds-eye view of the literature revealed (1) a wealth of information on the status of radiology in undergraduate medical education and (2) significant non-curricular experiences. The research question was simultaneously narrowed to focus on UME and broadened to incorporate learning beyond formal curricula: what is the current state of radiology education in U.S. medical schools.

Stage four: develop search strategy to find relevant articles

A comprehensive search was performed using five online databases: OVID Medline, Embase, ERIC, PsycInfo, and PubMed. The search strategy was developed in collaboration with an institutional librarian (Figure 1).
Figure 1: Literature Search Strategy for OVID Medline, Embase, ERIC, and PsycInfo Databases. Databases were searched from January 1, 2000 to December 31, 2023.

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For the Pubmed search, “medical student radiology education” was searched and the first 500 results were considered. Additional literature was obtained through manual exploration of article citations and education-tagged articles on radiology journal websites, including Radiology, RadioGraphics, Academic Radiology, and Journal of the American College of Radiology. A single author (R.B.) read the abstracts of the results produced by this literature search to select works for full-text review according to pre-defined inclusion and exclusion criteria adapted from a published literature search of radiation oncology in undergraduate medical education (Dennis and Duncan 2010).

Inclusion criteria were published journal articles, editorial, letters, and conference abstracts describing radiology-related curriculum development, courses, electives, teaching interventions, tools, or learning experiences pertaining at least, in part, to U.S. medical students. Exclusion criteria included duplicate articles; articles wholly not written in English; articles pertaining exclusively to residents, fellows, attendings, non-medical student trainees in allied health professions, radiology technicians, and medical students in other countries.

**Stage five: analyses**

All works receiving full-text review that ultimately met inclusion criteria and were not excluded were analyzed, with summary points and themes extracted for each article noted in an Excel document.
Stage six: reflexivity

The primary researcher in this study, R.B., is a medical student without significant expertise in radiology. This review therefore is largely contextualized by the literature and R.B.’s experiences with radiology through formal pre-clinical and clinical courses as well as online resources. Owing to his limited years of training, R.B. does not possess lived understanding of changes in the field to inform analysis of the ten-year period at this study’s focus.

Statistical Methods

Statistical methods were not utilized in data analysis for this study. Quantitative statements regarding information from the studies reported herein are borrowed from their respective works with close attention to correct contextual interpretation.
RESULTS

Overview

The literature search returned 447 studies from OVID Medline, Embase, ERIC, and PsycInfo databases. A Pubmed search of “medical student radiology education” returned 2,867 articles, of which the first 500 were considered. A search for “education” or education-tagged works on prominent radiology journal websites returned 313 education-tagged articles (Academic Radiology - 127, Journal of the American College of Radiology - 60, Radiology - 27, Radiographics - 100). From these three searches, 280 total works met criteria for inclusion in analysis, with additional literature uncovered through exploration of citations.

Subsequent thematic analysis revealed eight major trends in medical student radiology education: (1) integration of radiology into earlier phases of medical school curricula, with most schools not requiring a distinct preclinical or clinical course experience in radiology; (2) transformation of radiology clerkship and elective activities into more active, self-directed learning experiences; (3) heightened curricular emphasis on non-interpretive imaging skills; (4) incorporation of standardized radiology curricula into institutional educational activities; (5) shift to virtual radiology clerkship and elective activities during the COVID pandemic, with persistence into the post-pandemic era; (6) emergence of digital and microlearning tools supplementing formal education; (7) creation of extracurricular radiology experiential learning opportunities; and (8) discussions of radiology trainee diversity and imaging care disparities (Figure 2).
The first three themes—integration of radiology into earlier curricula, active learning in radiology courses, and emphasis on non-interpretive imaging—are discussed briefly here. The remaining five themes are explored in dedicated sections.

Integration of radiology into earlier curricula is robustly reported in other reviews. In their perspective piece, Farmakis and colleagues review published integrated preclinical and clinical radiology curricular reports and propose methodology for implementing an integrated curriculum (Farmakis et al. 2023). Separately, Goldman and colleagues discuss

Clinical experiences of students on the radiology service are often passive compared to the sub-internships they are required to undertake in medicine, surgery, pediatrics, or another field, in which they are expected to perform just below the level of the intern—writing notes, placing orders, and arranging follow-up for patients with a substantial degree of autonomy (Newbury et al. 2021). In recognition of this, a number of institutions have implemented more hands-on clinical rotations and electives fostering experiential learning. Elements of these courses can include students previewing and/or dictating live radiographic examinations (Huang et al. 2021, Newbury et al. 2021) and gathering clinical history for the radiology team (Dako & Awan 2021, Naeger et al. 2013). While the need for active radiology learning is apparent (Lakhani et al. 2023), and individual works describing active learning are scattered in the literature, few studies report on the prevalence and outcomes of such practices in U.S. medical schools.

Most medical student radiology education emphasizes imaging interpretation with the majority of interpretation focused on radiographs (references). In their findings from the ACR/AMSER survey, Straus and colleagues shared noninterpretive skills that radiologists and medical school Deans found important for student mastery, including appropriate imaging ordering and patient safety (Straus et al. 2014). 92% of residency program directors—in emergency medicine, family medicine, internal medicine, pediatrics, and general surgery—surveyed by Kondo and Swerdlow in 2011 agreed that
appropriate imaging ordering for common clinical scenarios was an essential skill for residents (Kondo & Swerdlow 2013). However, in their 2015 needs assessment for standardized medical student imaging education, Webb and colleagues found that only 60% of surveyed schools introduced students to ACR Appropriateness Criteria, which are fundamental to appropriate and safe imaging ordering for patients (Webb et al. 2015). In practice, the outcomes of this lack of education are grim–20-50% of imaging tests ordered are estimated to yield little or no clinical benefit (Litkowski et al. 2016). Moreover, inappropriate imaging can expose patients to the risks of radiation, contrast, and sedation or anesthesia. A scarcity of literature is concerned with long-term benefits of radiation science education, and short-term data from single institution studies is limited with small sample sizes (Kok et al. 2017, Koontz & Gunderman 2012, Linet et al. 2021). Altogether, this provided a strong rationale for bolstering radiation science education in medical schools for Linet and colleagues, who proposed a list of radiation science topics and ideas for educational strategies (Linet et al. 2021). A similar justification exists for providing more education to medical students on appropriate imaging utilization, cost and economic considerations of imaging. In their 2022 national student survey, Rohren and colleagues found that 65% of students had never heard of the ACR Appropriateness Criteria and 33% had heard of it but never used it (Rohren et al. 2022), despite the ACR Appropriateness Criteria being a valuable tool for improving student knowledge of appropriate imaging utilization (Dillion et al. 2010, Leschied et al. 2013, Stein et al. 2016). As with radiation science education, few works study the long-term benefits of imaging appropriateness education, and those that do are often limited by low sample sizes at single institutions. In recognition of the need to augment non-interpretive skill
teaching, the ACR developed Radiology-TEACHES, an online portal requiring students to progress through clinical cases and simulate ordering imaging studies (Willis et al. 2020). The ACR Appropriateness Criteria are integrated in the platform to further student understanding. With positive results from learners after implementation at eight medical schools, the program is a promising standardized educational resource for teaching medical students non-interpretive skills in radiology.
Standardized Curricula

With heterogeneous curricula and clinical rotation/elective offerings across the U.S., there has long been a call for a robust standardized radiology curriculum reflecting knowledge required of all graduating medical students. Until the early 2000s, there had been no requirement even for individual departmental elective radiology offerings, let alone established national radiology curricula (Lewis & Shaffer 2005). As the LCME crafted accreditation standards including educational objectives (ED)—with ED-17 specifically requiring educational opportunities be offered in diagnostic imaging for general medical practice—the national curriculum had the potential to support fulfillment of this standard alongside providing teaching and learning resources for a standardized radiology education (Gadde et al. 2022). AMSER resolved to develop such a curriculum in 2000, and five years later published a report of what to teach (with learning objectives), a standardized format for each section of the core curriculum, curriculum resources to aid in the development of medical school courses and rotations, and a shortlist of must-recognize imaging diagnoses (Lewis & Shaffer 2005). This original curriculum was made public on the AMSER website and designed to be covered in over four years of medical school. The AMSER National Medical Student Curriculum focused on medical imaging concepts relevant to all students regardless of their desire to pursue radiology specialty training. It was an outline with content to be fleshed out by educators at their respective academic medical centers. Modifications to the curriculum occurred in 2009, 2010, and 2012, without major structural changes (Gadde et al. 2022). Years later, in their 2014 ACR/AMSER white paper on medical imaging education, Straus et al. surveyed U.S. allopathic radiology chairs and medical school deans on education at their
institution, reporting that 25% of chairs (and 54% of deans) requested the development of consensus resources for student radiology education and cited the need for a national standardized curriculum. This perceived need for a standardized curriculum was accentuated by the same-year national needs assessment survey and literature review performed by Webb and colleagues (Webb et al. 2014). They found few available resources to guide educators in adding imaging content to medical school curricula. The needs assessment also revealed that a minority of medical school deans and radiology chairs used the AMSER Curriculum to revise their institution’s radiology teachings. Finally, they proposed a skillset to frame a national curriculum in radiology.

In addition to their National Medical Student Curriculum, AMSER debuted an online examination tool through Radiology ExamWeb in 2013 (Lewis et al. 2013, Reddy et al. 2015). The site included a multiple-choice question database with National Board of Examination (NBME)-formatted, peer-reviewed items based on their national curriculum that educators could use for their own examinations. Unlike other specialties that administer NBME shelf examinations to assess medical students, radiology does not have a shelf examination. Radiology ExamWeb (Association of University Radiologists 2024) was thought to fill the need for high-quality standardized questions for student evaluation. Within years of its launch the system grew to have 3,500 registered students from 6,500 institutions and 1,800 active questions (Lewis et al. 2013). In a collaborative effort between the ACR and AMSER, the Radiology ExamWeb database has since been transferred to the Standardized Tool for the Assessment of Radiology Students (STARS). The content has since blossomed to 2,800 edited questions (American College of Radiology 2024).
In 2020, for the first time since 2012, AMSER revised the National Medical Student Curriculum to address changes in the field of radiology that transformed radiology teaching (Gadde et al. 2022). The updated AMSER Curriculum sought to capture core concepts that all graduating medical students are required to know. Emphasis was placed on non-interpretive topics such as normal anatomy and “can’t miss” radiologic findings, removal of advanced topics more relevant for radiology residents and subspecialists, and topical and structural alterations to reflect contemporary organization of radiology departments and changing medical school curricula. The AMSER Curriculum continues to function as an outline of core radiology topics—basic imaging physics, limitations of modalities, contrast media, orientation to the radiology department, radiation safety, imaging in special populations, “risks” of radiology, financial cost—and delineates organ-based subject matter, resources, a diagnostic short-list, and goals and objectives (Gadde et al. 2020). A list of learning objectives for use in different medical school settings, including pre-clinical years, general radiology courses, and subspecialized electives, accompanies the curriculum (Association of University Radiologists 2024).

Interpretations of the AMSER Curriculum in the literature are directed toward practical use. Straus and colleagues suggest tailoring the AMSER Curriculum to each medical school rather than implementing it exactly as written (Straus et al. 2014). Naeger and colleagues illustrate ways to incorporate AMSER’s learning objectives from the pre-clinical phase through the remainder of medical school (Naeger et al. 2014). The AMSER Curriculum has borne online learning resources used widely. In 2005, Dartmouth began publishing interactive virtual patient cases based on the AMSER Curriculum through Case Oriented Radiology Education (CORE) (Chorney & Lewis 2011). This has grown
to 21 cases that can be readily accessed through the online teaching course Aquifer Radiology (Aquifer 2024). Aquifer is used by over 96% of U.S. allopathic medical schools and 70% of U.S. osteopathic medical schools (Aquifer 2024).
Virtualization and the COVID-19 Pandemic

In March 2020, the COVID-19 pandemic swiftly upended the traditional medical student educational paradigm reliant upon in-person learning. The AAMC recommended suspension of medical student clinical rotations (Association of American Medical Colleges 2024), effectively requiring radiology clerkships and electives to restructure to a virtual format to comply with social distancing and COVID-19 mitigation policies (Association of American Medical Colleges 2024). With this transition came opportunity for radiology educators to redefine medical student course experiences across the country.

Through surveys distributed to AMSER faculty and U.S. allopathic medical students in late 2020, Smith and colleagues evaluated this impact of the pandemic on radiology medical student courses (Smith et al. 2022). They found that faculty teaching virtual radiology courses used more pre-existing web-based materials, incorporated more pre-recorded didactic lectures, and reduced workstation readouts compared to traditional on-site rotations. Real-time didactic faculty lectures were the most common and also the highest rated by students, with pre-recorded didactic lectures and workstation readouts the next best-rated activities. Faculty enjoyed online teaching but had a strong preference for educating on-site. Students similarly preferred on-site education though reported online courses were still effective. Furthermore, the survey revealed that course directors were planning to expand online resource utilization during on-site rotations as well as increase virtual participation of faculty/students and pre-recorded lectures for student review. Based on their findings, the authors argued that hybrid courses—combining on-site and online experiences—may optimize learning in the future educational landscape.
Amidst this changing landscape, exploration of educational strategies and approaches best suited to the virtual environment have become paramount. In their *RadioGraphics* overview of resources for virtual radiology education, Fotos and colleagues iterate the importance of maximizing purposeful engagement in asynchronous (e.g., online modules, recorded didactics) and synchronous (e.g., live lectures, flipped classrooms, virtual readouts) activities (Fotos et al. 2021). Interactive learning tools, such as multiple-choice questions to foster critical thinking about recorded lecture material and think-pair-share to promote peer breakout room discussion during a live Zoom conference, are critical for increasing retention and synthesis of information in a remote learning environment (Subramanian et al. 2012, Owan 2021). Evidence-based learning principles—active retrieval, spaced repetition, deliberate practice, and growth mindset, to name a few—can be practically incorporated into the virtual milieu to enhance medical student radiology training (Tung and Matalon 2023).

A panel of faculty in the “COVID: Faculty perspective” Task Force of the Association of University Radiologists Radiology Research Alliance describe technology tools and educational considerations for incorporation into radiology (McBee et al. 2023). They discuss strategies for implementing virtual readouts, chat functions, video lectures, audience response systems, polling, gamification, QR codes, case collections, short educational videos, and podcasts, among other techniques. For medical student education specifically, they identify several common elements for success in remote radiology courses:

- Clear educator-student communication, from expectations to check-ins
- Structured schedules with daily assignments defined
• Dedicated student lectures
• Student participation in radiology resident conferences, tumor board, and teaching conferences
• Virtual readouts
• Review of unknown cases
• Use of group-response/polling
• Competency-based assessment

These elements are complemented by Smith and colleagues’ recommendations for online radiology teaching based on faculty and student survey results: engage students with interactive lectures; pre-record lectures for online access by students; promote independent student learning and reinforce with self-assessments, interpretation, and discussion; and encourage students to independently interpret images and subsequently present their findings to faculty for feedback and focused teaching (Smith et al. 2014). Together, these constitute evidence-based and expert-endorsed guidelines for structuring partially or fully remote radiology courses for medical students.

With the rise in asynchronous learning necessitated by COVID-19 pandemic transformations to medical education, high-quality online learning tools are more important than ever. Medical student radiology course directors can curate the learning environment for their students using extensive UME-focused resources vetted by the radiology education community (Table 2) (Belfi et al. 2021, Farmakis et al. 2023, Gomez et al. 2020, McBee et al. 2023, Smith et al. 2022). For advanced and subspecialized rotations—perhaps, in many cases, more relevant for the radiology resident—a compilation
of free open access “meducation” radiology resources (#FOAMrad) organizes each resource by topic to streamline learner utilization.

Reports of COVID-19 pandemic-precipitated changes to medical school radiology courses are widely published. These encompass virtualization of radiology core clerkships (Durfee et al. 2020, Goldenson et al. 2022), general radiology electives (Belfi et al. 2021, Gomez et al. 2020), subspecialty radiology electives (Smith & Boscak 2021), interventional radiology electives (DePietro et al. 2021) including those accessible worldwide (Mills et al 2023), multi-institutional imaging appropriateness electives (Francis et al. 2023), and hybrid radiology clerkships (Musick et al. 2023). Several examples are highlighted below:

At the Johns Hopkins University School of Medicine, radiology education leaders developed a 3-week remote diagnostic radiology elective for medical students in response to the pandemic. The course exhibited a 10-fold increase in enrollment compared to the traditional in-person offering (Gomez et al. 2020). In addition to reaching a greater number of students, it opened access to those in earlier stages of medical school. The virtual elective eliminated shadowing and in-person workshops, substituting them with recorded lectures, live Zoom didactics, interactive remote workshops and case sessions, virtual office hours, and online quizzes and jeopardy sessions. Microsoft Teams functioned as a homepage for course-related messaging, Zoom lecture links, and real-time conversations between students and instructors. Blackboard organized course materials including lecture slides, assignments, and links to online resources.
At Weill Cornell Medical College, a 2-week introductory radiology elective was transitioned to a completely remote format using asynchronous (e.g., internally-developed open-source online modules) and synchronous (e.g., remote lectures, interdisciplinary conferences, student-prepared virtual readout sessions) activities (Belfi et al. 2021). The online modules contextualize the use of imaging with patient encounters while reviewing radiologic anatomy, basic image interpretation, and safety (Belfi et al. 2022). Belfi and colleagues thoroughly describe the daily schedule with specific online learning assignments, details of conference and lecture organization, structure of virtual readout sessions, and other course components. In sharing their course curriculum, they aim to allow other institutions to adopt similar radiology course elements for their students.

At the Duke University School of Medicine, Musick and colleagues devised a remote learning clerkship model that was later converted to hybrid (Musick et al. 2023). Approximately half of the hours entailed in-person subrotation time spent observing and participating in patient rounds, procedures, imaging studies, and case readouts. The remaining half was dedicated to live virtual didactics, pre-recorded lectures, interactive virtual workshops and mock dictations, guided review of archived cases, and virtual case presentations, with variation in activities across subspecialty rotations. Compared to solely in-person or remote curricula, the hybrid radiology clerkship curriculum improved student satisfaction without changing student performance. Authors recommended, based on their findings, that hybrid models maintain in-person immersive experiences over video-conference readouts. The former advantageously fosters personal relationships
with peers and faculty, features direct observation of radiology activities and the live unfolding of cases, and permits participation in interventions.
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**Table 2: State-of-the-Art Resources for Contemporary U.S. Medical Student Radiology Education.**
Digital and Microlearning Tools

The medical trainees of today are largely millennials. The precise time frame defining the generation is variable, but some professional demographers use birth years between 1982 and 2001 (Scardamalia 2022). As “digital immigrants,” millennials grew up amidst the rise of technological innovations and social media, and accordingly have unique educational preferences and needs. Millennials are comfortable with immersive technology and multimedia learning, through which they desire active engagement (Chen & Scanlon 2018, Griffith et al. 2019, Lourenco & Cronan 2017, Scardamalia 2022). They possess high expectations for success, benefit from goal-setting and clear performance benchmarks, and seek out continuous feedback. Collaboration, entertainment, instant access to information, and multi-tasking are highly valued in a learning environment (Shah & Kotsenas 2017, Slanetz et al. 2013). Over the past two decades, radiology education has reflected these millennial educational characteristics in emerging teaching techniques:

- Audience response systems increase learner engagement and provide immediate feedback (Richardson 2014, Streeter & Rybicki 2006).
- Digital radiology case files offer immediate feedback and rely on collaboration to develop (Alvarez et al. 2006, Balkman & Loehfelm 2014, Gentili et al. 2007, Lilly et al. 2020, Roth et al. 2005)
- Flipped classrooms leverage technology to review material preclass and focus class time on interactive application (Belfi et al. 2015, Restauri et al. 2017).
- Podcasts and vodcasts teach on-demand portable content for learners on-the-go, enabling multi-tasking and personalized control over content progression (e.g., stopping, fast-forwarding, rewinding) (Frederick & Gibbs 2022, Menashe et al. 2014).
- Virtual reality technologies facilitate experiential learning and beget a high level of active learner participation in a format familiar from gaming and entertainment (Uppot et al. 2019).

The millennial generation almost universally engages with the surrounding world through social media. Social media platforms not only allow for content creation, information sharing, and social connection, but also serve as effective tools for education and professional activities (Júdice de Mattos Farina et al. 2023, Shah & Kotsenas 2017). Advantages of social media in the radiology educator space include the ability for widespread dissemination of educational information to maximize impact, as well as generation of content more readily accessible for today’s learners (Griffith et al. 2019). However, social media has potential disadvantages related to privacy, work effort, and trust (Shea Johnstone & Towbin 2022). Regardless of the platform, radiology information-sharers—including students—should take several steps to maintain ethical conduct and patient privacy: using de-identified images, avoiding posting “sensational” cases, being mindful of maintaining professional behavior, storing images securely, and
seeking patient consent if posting a rare case. They should spend significant time preparing and verifying content to prevent the spread of misinformation (Shea Johnstone LAG & Towbin 2022), and recognize that it can be difficult to gauge learner understanding of their content (Ranginwala & Towbin 2018).

Numerous social media platforms are used within the radiology community—including X (formerly known as Twitter and the most popular), Instagram, LinkedIn, Facebook, Youtube, TikTok, Figure 1, Twitch, Discord, Doximity, Radiopaedia, and ResearchGate (Júdice de Mattos Farina et al. 2023, Ranginwala & Towbin 2018, Shah & Kotsenas 2017). Among their many differences, social media platforms vary in their character limits for posts, suitability for image-sharing, maximum video length, response and comment formats, and support for clickable links (Shah & Kotsenas 2017). In selecting an appropriate social media platform, radiologists should consider platform-specific characteristics and fit for the content they seek to deliver (Ranginwala & Towbin 2018).

For medical students, social media allows for interactive engagement with radiology learning. The COVID-19 pandemic has accelerated the building of social media learning resources. YouTube contains videos for learning radiology principles as well as guidance for a career in the field (Shah et al. 2021). Instagram is built around images and is useful for educators sharing teaching cases as well as radiology residency programs showcasing photos and videos of their community and residents’ day-to-day experiences. Like YouTube and Instagram, X is a source for radiology content and residency information. It also provides opportunities for networking, mentorship, collaboration, advocacy, and brand cultivation (Shah et al. 2021, Shah et al. 2021). Students can follow hashtags such as #futureradres (Future Radiology Residents), #radtwitter, and #FOAMRad (Free Open
Access Meducation) to access Tweetorials (Twitter tutorials), see event advertisements for topical webinars and residency program open houses, and find potential mentors. Following the @CasesCookyJar account and #mathurminute exposes the learner to cases with targeted teaching points (Sailer et al. 2023). Several highly-followed accounts, including @futureradres, generate content providing career guidance for students interested in the field (Shah et al. 2021). Journals such as *RadioGraphics* and *Radiology* also engage with social media, using Tweetorials and YouTube videos to highlight key points of recently published works, as well as maintaining Facebook and Instagram accounts advertising journal events and opportunities, among many other social media endeavors (Bunch & Tomblinson 2022, Júdice de Mattos Farina et al. 2023).

Much of the learning that occurs through social media can be conceptualized as microlearning. Microlearning tools deliver education in bite-sized quantities (Chen et al. 2022). These tools can speedily introduce new information (e.g., through an Instagram image of a radiologic sign unfamiliar to the learner) and also enable deep dives (e.g., through a Tweetorial on a focal area of interest) (Sailer et al. 2023). Short videos, including those published on YouTube by popular channels such as @yaleradiology, also deliver “just-in-time” content to learners (McBee et al. 2023). Learners should be wary of information given the lack of peer review on social media and follow credible accounts (e.g., radiology societies and journals, professional radiologists). Together with more comprehensive resources and experiences (e.g., formal courses, textbooks), as well as learning strategies to promote long-term retrieval (e.g., spaced learning using a flashcard system like Anki), social media microlearning can effectively round out a learner’s educational “toolbox” (Sailer et al. 2023).
**Extracurricular Learning Experiences**

The formal medical school curriculum is only one aspect of the medical student educational experience. Noncurricular opportunities contribute to the “hidden curriculum” that can tremendously shape trainee perceptions of radiology and professional identity development (Hafferty 1998, Majumder et al. 2021). Medical students have various avenues for deepening their understanding of the radiology landscape outside of course experiences.

Several institutions have programs employing medical students as call assistants in the reading room. In 2005, Yale developed a hands-on experience for medical students with more than 6 months of clinical clerkship experience to work with emergency department radiologists to triage and manage off-hour clinical and administrative tasks, such as answering phone calls and fielding inquiries from clinicians (Kennedy et al. 2010, Davis et al. 2011). Based on a presentation of this program given by Yale faculty, Dartmouth created their own using third- and fourth-year medical students to streamline imaging workflow for on-call radiology residents by carrying the trauma pager and answering calls from clinicians, radiology technicians, and other hospital personnel (Chen & Lewis 2014). The University of Maryland also has had an Emergency Radiology Triage Assistant Program (ER-TAP) since 2010 modeled after the Yale Department of Radiology with medical students from all class years involved (Haver et al. 20223) At the University of Iowa, 3rd year medical students can work as externs, responding to pages on the general radiology pager, coordinating study requests with clinicians and technologists, and relaying imaging interpretations (Dobre et al. 2012).
A 2018 report on the current status of radiology call assistant triage programs found that six of them employed third- and fourth-year medical students as triage assistants, with student wages ranging from $10 to $30/hour. Medical students benefited through increased understanding of the practice of radiology and greater interest in pursuing radiology as a career (Ngo et al. 2018). Within the past five years, inspired by other academic medical center descriptions of success using medical students as call triage assistants, the Hospital of the University of Pennsylvania too adopted a student triage program (Levy et al. 2020). Most recently, beginning in April 2021, the Icahn School of Medicine at Mount Sinai has trained third- and fourth-year medical students as reading room coordinators (RRCs) to decrease the burden of non-interpretive tasks of radiology residents on call by triaging phone calls and communicating critical findings to providers (Gillingham et al 2024).

Radiology research is another well-documented means for exposing medical students to radiology and enhancing their interest in the field (Shah et al. 2019, Whitworth et al. 2013). Formal programs can enrich the support for student radiology research. At Massachusetts General Hospital, a resident-led medical student radiology research group pairs students with resident and faculty members to create a ladder-mentoring program requiring less of the faculty advisor’s time. The resident guides the student through the research process from identifying clinical problems and crafting research questions through writing and revising manuscripts for publication (Som et al. 2021). At the Perelman School of Medicine at the University of Pennsylvania, the Department of Radiology funds radiology research projects for medical students in a formalized program during the summer before second year. Students are matched with mentors
based on students’ statement of interests and curricula vitae, meetings and booklets showcasing available projects, and one-on-one faculty-student discussions. At West Virginia University, a resident managed peer-mentoring program exists in which a resident identifies projects which medical students at different levels of research background and training can undertake, with the resident and student having regular check-ins and oversight from faculty (Lakhani et al. 2022). Collectively, these programs increased student knowledge of research and the specialty of radiology.

For more than a decade, medical students have also immersed themselves in radiology through global health. These experiences include domestic and international outreach projects supporting underresourced communities and sustainable capacity-building, such as those through RAD-AID International (Isaac & Awan 2023). RAD-AID is a non-profit charity organization that began in 2008 to bring radiology and imaging technology to resource-limited regions globally. It comprises more than 14,000 radiology professionals from 146 countries, serving 91 hospitals in over 40 countries (RAD-AID 2024). The organization has seen a substantial growth in medical student and radiology trainee involvement since its founding, with more than 80 ACGME-accredited affiliated academic medical centers (England et al. 2021). Through RAD-AID, students can participate in a program to earn a Global Health Radiology Medical Student Training Certificate and can go on to participate in a field project locally or abroad (RAD-AID 2024). They obtain thorough understanding of radiology’s role in global health, radiology issues in underserved regions, and methods for introducing and maintaining radiology projects. Other global strategies further radiology education and involving medical students are Health4theworld—which aims to bring “free online reliable education in
medicine to remote parts of the world (Health4TheWorld 2024)–and Road2IR–a collaboration between Muhimbili University of Health and Allied Sciences (MUHAS), Yale Department of Radiology and Biomedical Imaging, Emory Department of Radiology and Imaging Sciences, and other partnering institutions “to build self-sustaining IR training programs in East Africa” (Road2IR 2024).

Locally, medical students can participate in their institution’s radiology student interest group. Where such groups do not exist, radiologists can help create them, and where they do, radiologists can contribute to the quality of their programming (Fricke and Gunderman 2010). For student interest group leaders, these groups are opportunities to network and build connections within the institution’s radiology department, develop radiology knowledge and skills, and create spaces for their peers to learn about the specialty as well. Reaching out to upperclassmen can provide insight into navigating local radiology opportunities (including shadowing and research–both invaluable ways for improving understanding of the field), electives/rotations, and the residency application process (Nguyen et al. 2022).

With local engagement in radiology comes opportunities for mentorship. Prior to the COVID-19 pandemic, mentoring in radiology most commonly occurred within an academic institution or clinical practice. However, with the pandemic catalyzing the use of online platforms for real-time interactions globally, the landscape of mentoring has expanded extramurally to include professional societies, journals, and social media (Lee et al. 2023). After the onset of the pandemic, Gupta and colleagues conducted a national radiology mentorship program (Gupta et al. 2022). They distributed surveys through the Society of Pediatric Radiology and social media (X, Facebook, and Reddit) to match
mentees with mentors. The program fostered inclusivity for all participants regardless of location or background, notably with women and students under-represented in medicine exhibiting high satisfaction.

On a state- and national-level, students can get involved with larger radiology societies and attend conferences. For example, students can get free membership through the Radiological Society of North America (RSNA) and serve on committees, such as the RSNA Medical Student Take Force (MSTF), advocating for radiology policy and education (Ballard et al. 2020, Shah et al. 2021). They may also participate in mentored experiences through RSNA journals (e.g., Trainee Editorial Boards such as RadioGraphics TEAM), and apply for grants to fund trainee research. By attending the RSNA Annual Meeting, students can look out for trainee-tagged courses and activities hosted by the RSNA Medical Student Task Force (MSTF) among the wealth of educational sessions, network at receptions and organizational events, and explore the intersection of radiology with industry and innovation in the Technical Exhibit halls and at vendor demonstrations (Zaki-Metias et al. 2023). Students can also join the nationwide virtual radiology student interest group called Radiology Student Interest Group (RadSIG) to deepen their awareness of and interest in the field (Vayani et al. 2023).

Ultimately, through these involvements, students not only can further their exploration of radiology but also hone skills as advocates for the specialty that they may build on for the rest of their careers (Kim et al. 2023).

Students especially interested in interventional radiology can leverage a range of opportunities to become more informed about the specialty. From partaking in specialty-specific global health educational outreach (McKenney et al. 2021), to leading
interventional radiology student interest groups, to attending medical student symposia (Sprout et al. 2023), to joining the Society of Interventional Radiology Resident, Fellow, and Student Section (SIR RFS) and IR Medical Student Council, students can explore organized educational activities and resources in the field (Goldman et al. 2018).

In summary, extracurricular endeavors abound for students drawn to radiology. Though specific opportunities vary across institutions, students may seek out participation in a triage assistant program, formal and informal research opportunities, global health outreach through programs such as RADAID, and local interest groups and shadowing. In the virtual era, mentorship across a multitude of venues and involvement in national interest groups, societies, and conferences with student programming are highly feasible. Students with specialized interest in interventional radiology have myriad opportunities for career exploration as well.
Trainee Diversity and Health Equity

Diversity is a critical component of the U.S. healthcare system. Racial diversity has been steadily increasing in the U.S., with 2020 estimates by the U.S. Census Bureau of 57.7% White, 18.7% Hispanic or Latino, 13.4% Black or African American, and 6.0% Asian (United States Census Bureau 2024). Improving diversity in the physician workforce has the potential to reduce health care disparities, particularly among women and racial minority groups (Jackson & Gracia 2014, Saizan et al. 2021). Increased diversity also may improve patient-provider communication and advocacy, thereby bettering health outcomes (Awosogba 2013, Institute of Medicine 2003, U.S. 2006). Diversity, moreover, benefits the educational environment (Awan 2021).

Within radiology, there are significant imaging care disparities with multiple causal patient and provider factors (Abraham et al. 2021, Betancourt et al. 2019). These disparities include breast and lung cancer screening (Abraham et al 2021, Davis et al 2021), imaging ordering (Waite et al. 2021), and standard-of-care interventional radiology procedures (Kumar et al 2019), among other disparities in imaging care (DeBenedectis et al. 2022).

Over the past few decades, in an attempt to highlight the impact of diversity on health care disparities, the academic radiology community has reported on the underrepresentation of women and minority groups. A 2014 study focused on resident diversity reported that U.S. diagnostic radiology programs rank 17th for female and 20th for underrepresented minority representation among the 20 largest specialty areas (Chapman et al. 2014). During the prior eight years, there was no significant increase in female or underrepresented minority resident representation in diagnostic radiology. A
2020 study investigating faculty diversity illuminated a decreasing proportion of women with increasing academic ranks within each year and disparity in Black and Hispanic faculty representation (Niu et al. 2020). In 2022, Wu and colleagues evaluated different levels of the academic radiology workforce for changes in diversity over time, also finding that the low representation of Black and Hispanic radiology faculty is observed at all levels and unchanging (Wu et al. 2022). The study similarly found decreasing proportions of women with increasing seniority of faculty position (38% of radiology instructors were female, compared to 22% of professors and 17% of department chairs). The most staggering change in percentage of female trainees occurred from medical school matriculants (52%) to radiology residency applicants (29%), without significant change between 2010 and 2019. Promisingly, in a study published the following year, Wu and colleagues found improving representation of Black and Hispanic radiology residents compared to other specialties, with respective increases from 2011 to 2021 of 3.1% to 3.8% and 4.8% to 7.4%, though still significantly lower than the corresponding percentages of first-year Black and Hispanic medical students—11.3% and 12.7% (Wu et al. 2023, Association of American Medical Colleges 2024).

In response to the findings in Wu’s initial study, Pandharipande et al. argued that, in order to effect change, women earlier in their careers must have mentors, sponsors, and allies to advocate for better workplace conditions (Pandharipande et al. 2022). Overall, they described current efforts to diversify the radiology workforce as insufficient, recommending further research to identify and target programs that work best to effect positive change. The same year, Klontzas et al. offered their perspective on how to increase diversity in the radiology trainee workforce. In the residency applications
process, they recommended increasing awareness of unconscious bias, promoting holistic application review (also a focus of DeBenedectis et al. 2020’s guide to cultivating diversity in residency recruitment), continuing virtual interviews, improving role model visibility, increasing exposure to radiology, and showcasing departmental commitment to diversity, equity, and inclusion (DeBenedectis et al. 2020, Klontzas et al. 2022). In alignment with this, Yuan et al.’s 2018 preliminary report of educational interventions at the University of Massachusetts Medical School concluded that required visibility of female radiologists and active publicity of female radiologists from the first preclinical year are likely to increase female medical student interest (Yuan et al. 2018). Of note, early exposure in the preclinical curriculum and patient-centered electives only minimally increased female interest, suggesting that early exposure alone is not sufficient. As a potential solution, several institutions have developed diversity visiting student clinical experiences to encourage female and underrepresented group interest in the field (Dodelzon et al. 2022, Emory University School of Medicine 2024, University of Colorado 2024). At Cornell, a four-week virtual radiology internship providing clinical radiology and career exposure to underrepresented minority students in radiology resulted in a significant shift in perception of the field and declaration of interest in pursuing a radiology career among all student participants (Dodelzon et al. 2022).

Other works concern themselves with broader reasons for radiology health disparities, such as structural racism, and ways to get involved with medically underserved populations. In academic radiology, Antiracism Journal Clubs could improve understanding of the effects of racism and structural barriers in the field, and institutional leadership requiring antiracism and implicit bias education—in tandem with securing
appropriate resources and consistently evaluating performance—could effect equitable change in diversity, equity, and inclusion (Abraham et al. 2023). Karp et al. discuss the opportunities that radiology trainees have to positively impact individuals from medically underserved populations—from mobile mammography and ultrasound screening clinics, to remote or in-person mentoring, to local outreach projects (Karp et al. 2023).
DISCUSSION

The literature reporting on radiology education for U.S. medical students is vast, with 280 works identified in our comprehensive literature search alone. Several notable trends in the discipline have emerged within the past decade.

Medical schools have increasingly been integrating radiology into earlier phases of their curricula. Rationale for early and integrated radiology curricula is clear: such exposure improves basic knowledge of radiology and its relationship to medical practice, mitigates misconceptions of the field, increases confidence with ordering diagnostic studies, and enhances likelihood of pursuing radiology residency training (Arleo et al. 2016, Belfi et al. 2022, Di Salvo et al. 2014, Kraft et al. 2018, Leschied et al. 2013, Lim-Dunham et al. 2016, Ocal et al. 2023). Given broader shifts in undergraduate medical education toward longitudinal curricular integration and shortened preclerkship phases (Association of American Medical Colleges 2024), it is only befitting for radiology education to occur in a blended manner within multiple organ system blocks of preclerkship curricula and across rotations during clerkships (Belfi et al. 2022). However, without higher regulatory agency mandates on radiology curricula, the landscape of radiology education delivery is likely to remain heterogeneous.

At a number of institutions, radiology rotations have transformed from passive observational experiences in the reading room to active engagement with PACS, with significant benefits to student learning. It is time for the culture of radiology clinical rotations everywhere to adopt a paradigm involving student responsibility in radiologists’
care. As Lakhani and colleagues suggest, students could take on non-urgent cases from the work list, review the electronic medical record for clinical context, and draft a preliminary report (Lakhani et al. 2023). Not only would students feel a greater sense of autonomy in the reading room, but also they would develop a better sense of radiology as a specialty. Ultimately, such experiences would better their understanding of noninterpretive (e.g., imaging appropriateness, framing indications effectively) and interpretive skills (e.g., radiograph interpretation), though more single-institution reports of active radiology learning would be useful to unequivocally show its impact. In the meantime, radiology educational leaders and societies ought to collectively reimagine restructuring radiology rotations in this way and begin developing specific guidelines for institutional adoption (i.e., as they did with the AMSER curriculum).

Radiology education has shifted to focus more on noninterpretive skills that all future clinicians, regardless of specialty, need to know. Patient safety, imaging appropriateness, and costs and economic considerations of imaging are a few topics gaining traction in curricula. National tools such as Radiology-TEACHES and Aquifer have been developed, at least in part, to further the teaching of noninterpretive skills. Certain disciplines within the noninterpretive skill umbrella (e.g., radiation science education) have a need for larger scale curricular development (Linet et al. 2021). Others would benefit from greater evaluation of the effectiveness of their teaching tools—take imaging appropriateness and Radiology-TEACHES, for example—and retention of knowledge into residency training.

Since 2000, the AMSER Curriculum has been the primary national radiology curriculum outlining the essentials of imaging that medical students should learn. The AMSER
Curriculum includes a list of resources to guide the study of the objectives therein, and several articles have recommended strategies for the practical implementation of the curriculum (Naeger et al. 2014, Straus et al. 2014). In 2014, less than half of medical school leadership was incorporating AMSER in the creation of their local curricula. As AMSER-inspired educational platforms have risen to prominence (e.g., Aquifer Radiology), especially in the wake of 2020 updates to the AMSER Curriculum, curricular restructuring secondary to the COVID-19 pandemic, and increased dependence on virtual resources, there is a need for assessing the pervasiveness and utility of the AMSER Curriculum for radiology education. This would be a critical follow-up to the needs assessment for a standardized national radiology curriculum performed by Webb and colleagues ten years ago, to see how much progress has been made (Webb et al. 2014), especially as recent literature has hinted at the continued desire for a “collaborative and widely shared set of updated AMSER resources and interactive sessions” (Smith et al. 2022).

Extracurricular endeavors abound for students drawn to radiology. Though specific opportunities vary across institutions, students may seek out participation in a triage assistant program, formal and informal research opportunities, global health outreach through programs such as RADAID, and local interest groups and shadowing. In the virtual era, mentorship across a multitude of venues and involvement in national interest groups, societies, and conferences with student programming are highly feasible. Students with specialized interest in interventional radiology have myriad opportunities for career exploration as well. Radiology educators can support student extracurricular
participation in radiology by creating and revitalizing the aforementioned programs at their home institutions coupled with dedicated student recruitment.

The underrepresentation of women and racial minorities within radiology is clearly established, with little evidence of improvement across levels of radiology trainees and faculty beyond a small increase in Black and Hispanic radiology residents over the past 10 years. While further research is necessary to demonstrate successful measures for addressing this lack of diversity at the medical student level, incorporating equitable changes into the radiology residency recruitment process, bolstering mentorship opportunities and faculty visibility, and implementing clinical experiences earmarked for underrepresented groups are promising solutions. Medical students (and educators) have the opportunity to address radiology health disparities at home through dismantling race-based structural barriers and helping medically underserved populations (e.g., by setting up breast and lung cancer screening programs, mentorship, and outreach projects).

Perhaps the most obvious recent movement in medical student radiology education has been the abrupt transition to remote learning during the COVID-19 pandemic. In the post-pandemic era, national surveys suggest that hybrid radiology rotations combining in-person and digital components may be ideal, capturing the advantages offered in each setting (Smith et al. 2022). Such curricula, specifically, could include a few days per week of direct observation and active participation in imaging interpretation and procedures on-site, with the remaining days spent in virtual didactics, readouts, and self-study using digital resources. In-person experiences provide greater understanding of careers and daily workflow in radiology necessary to inform students’ career choices along with their perceptions of radiology as future referring clinicians (Webb 2023).
Remote teaching through live and recorded didactics increases flexibility, convenience, and efficiency for educators while being well-received by students and suiting their preferences as digitally-immersed millennials. Musick and colleagues showcase the hybrid elective they developed at Duke and review best practices for the benefit of other radiology educators (Musick et al. 2023). Nevertheless, with hybrid radiology courses still in their early stages, much remains to be studied about their impact on trainee learning as well as optimization of the course environment for educators and students alike.

During the technological awakening in the 21st century, digital resources and social media have become powerful means for students to increase understanding of radiology and deepen their learning. With many lacking exposure to radiology in their formal medical school curricula, students can turn to the digital environment to interactively engage with the field, and, in turn, find mentors, research opportunities, and bite-sized teachings in radiology. Effectively utilizing digitally-augmented strategies, such as microlearning and spaced repetition, will enable them to make the most of their education (Sailer et al. 2023).

As the current crop of medical students evolves from millennials to generation Z, educators will need to adapt curricula to meet the latter’s needs and preferences for learning. In contrast to its attention to millennial learners, the literature has yet to substantially report on how the radiology community can improve the way it teaches generation Z. One viewpoint piece suggests incorporating online resources that complement in-person learning, personalizing education, creating novel digital assessments, centering generational values of diversity and social justice, and fostering
wellness in the learning environment (Cyphers et al. 2023). Radiology educators ought to not only borrow insights from other teachers of generation Z when reimagining education delivery for them, but also share their experiences and recommend best practices once generation Z dominates medical school enrollment nationwide.

As generation Z enters the radiology world, artificial intelligence (AI) is rapidly revolutionizing medicine. In radiology, AI applications have demonstrated potential to not only assist radiologists with image-based tasks such as abnormality detection and disease diagnosis, but also streamline clinical radiology workflow through improving study selection and protocolling, image acquisition, worklist prioritization, reporting, business processes, and resident education (Hosny et al. 2018, Tadavarthi et al. 2022). Reports of U.S. medical student perceptions of AI, however, show that 23-44% are concerned enough about the impact of AI on radiology (i.e., believing that AI will have negative effect on job prospects) that they are less likely to pursue residency training in the field (Atalay et al. 2023, Park et al. 2021, Reeder & Lee 2022). A meta-analysis of 21 works describing the impact of AI on the attitudes of students across the globe—as well as radiology residents and radiologists—found that 70% of students and 82% of radiology trainees and radiologists supported the inclusion of AI training in medical curricula (Hassankhani et al. 2024). Moreover, in their study surveying medical students at 32 different schools, Reeder & Lee found students’ most preferred way to learn about AI in medical school is through radiology rotations followed by pre-clinical lectures (Reeder & Lee 2022). It is thought that formal AI education may combat misinformation and mitigate students’ negative perceptions of AI (Hassankhani et al. 2024, Hathaway et al. 2023, Park et al. 2021, Reeder & Lee 2021), with one study in the UK demonstrating that
students receiving AI education are more likely to be interested in a career in radiology (Sit et al. 2020).

It is therefore essential for medical students to receive education on AI in medical schools to not only correct misconceptions and properly inform medical students’ career choices, but also equip clinicians to succeed in a future of healthcare in which AI will take on a prominent role inside and outside of radiology (Hassankhani et al. 2024, McCoy et al. 2020). Medical schools will need to imbue the education of AI into their curricula and extracurricular offerings to promote awareness of AI’s possibilities, realities, and limitations as its roles in medicine evolve. This may best be accomplished in an integrated and interdisciplinary fashion, with special attention to students experiencing AI integration in real-life clinical workflows to ground their understanding of its role in clinical practice (Hassankhani et al. 2024, McCoy et al. 2020). There are only a handful of reports of AI curricula for radiology residents (Garin et al. 2023), and according to a 2021 scoping review, a critical shortage of studies describing AI curricula for medical students with few cases of piloted programs and none reporting on learner outcomes (Lee et al. 2021, McCoy et al. 2020, Paranjape et al. 2019). To promote delivery of AI curricula for medical students, medical educators ought to create a standardized framework for core objectives of AI training, develop and refine such curricula, and share their findings to advance curricular development elsewhere for medical students (Lee et al. 2021). Furthermore, radiology educators may consider repurposing published AI curricula for radiology residents to meet the needs of medical students. As such curricula deploys, future research will be necessary to identify best practices and facilitate widespread implementation.
CHALLENGES & LIMITATIONS

The results and implications of this thesis are fundamentally limited. As a state-of-the-art review, the information highlighted herein is most specific to the ten-year period between 2014 and 2023, leading to potential misrepresentation of the broader development of radiology education for medical students over time (Grant & Booth 2009). In recognition of this shortcoming, this thesis attempts to contextualize its contemporary findings with relevant overviews of the history of radiology education in its introduction and theme-specific history in results. Furthermore, in our search strategy, we may have missed works potentially relevant to this review. We iteratively refined our search strategy to encompass keywords and key databases until we found the results comprehensive. To further minimize failure of inclusion of relevant literature, we also searched education-tagged articles in prominent radiology journals and reviewed article citations for pertinent works. Additionally, we excluded works reporting entirely on populations similar to U.S. medical students, such as U.S. radiology residents and fellows as well as foreign medical students. We limited our scope to U.S. medical students in accordance with the stated aims of this work and in recognition of the substantial representation U.S. medical student education has in the radiology education literature. Further research is needed to identify themes and trends in radiology education for these other populations. Finally, this work is predominantly authored by one individual (R.B.), a medical student without the field expertise of a radiology trainee or attending, or the perspective of an individual
long in the medical field. We have submitted this thesis for review by experts having such qualifications to improve the rigor of this work.
DISSEMINATION

The contents of this work have yet to be distributed to the scientific community. We plan to submit portions of our findings for presentations at radiology conferences including the RSNA annual meeting, as well as for publication in peer-reviewed radiology journals like Academic Radiology.
FIGURE REFERENCES AND LEGENDS

Figure 1: Literature Search Strategy for OVID Medline, Embase, ERIC, and PsycInfo Databases. Databases were searched from January 1, 2000 to December 31, 2023.

Figure 2: Themes in the U.S. Medical Student Radiology Education Literature.

Image created in Biorender.
TABLE LEGENDS


Table 2: State-of-the-Art Resources for Contemporary U.S. Medical Student Radiology Education.
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