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Invited Review

INVITED REVIEW

Physician preparedness for big genomic data: a review of genomic medicine education initiatives in the United States

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Abstract

In the last decade, genomic medicine education initiatives have surfaced across the spectrum of physician training in order to help address a gap in genomic medicine preparedness among physicians. The approaches are diverse and stem from the belief that 21st century physicians must be proficient in genomic medicine applications as they will be leaders in the precision medicine movement. We conducted a review of literature in genomic medicine education and training for medical students, residents, fellows, and practicing physicians with articles published between June 2015 and January 2018 to gain a picture of the current state of genomic medicine education with a focus on the United States. We found evidence of progress in the development of new and innovative educational programs and other resources aimed at increasing physician knowledge and readiness. Three overarching educational approach themes emerged, including immersive and experiential learning; interdisciplinary and interprofessional education; and electronic- and web-based approaches. This review is not exhaustive, nevertheless, it may inform future directions and improvements for genomic medicine education. Important next-steps include: (i) identifying and studying ways to best implement low-cost dissemination of genomic information; (ii) emphasizing genomic medicine education program evaluation and (iii) incorporating interprofessional and interdisciplinary initiatives. Genomic medicine education and training will become more and more relevant in the years to come as physicians increasingly interact with genomic and other precision medicine technologies.

Introduction

The completion of the Human Genome Project has revolutionized clinical approaches to diagnosis and, to a more limited extent, therapy. Genomic medicine has emerged as a field of growing utility, and various stakeholders, from patients to physicians, have taken interest in clinical- and consumer-based genomic tools (1–3). Today, 1 in 25 adults in the United States (U.S.) have personal genetic data at their fingertips (4) owing to the proliferation of low-cost direct-to-consumer genomic health tests and other genomic technologies. Patients and consumers view genomic data favorably (5), and intend to discuss genetic results with their physicians (6,7); physicians are expected to have genomic medicine content expertise in responding to patient queries.

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Although physicians hold largely positive attitudes toward genomic applications (8–10) and recognize the growth of genomic medicine and likelihood of their participation in the interpretation and communication of genomic data, physicians express discomfort interpreting and contextualizing genetic results (11). In fact, there is ample research suggesting that physicians are largely unprepared to use genetic and genomic data (11–18). For instance, physicians feel unprepared to order genomic tests (19), explain test results (10,20–22), and incorporate results into clinical practice (23). Additionally, physicians cite time barriers in integrating genomics (24). Meanwhile, the volume and nature of big data more generally in the clinical encounter is anticipated to grow beyond the interpretative capacity of physicians (25). Pressures from the health care system as well as the concerns over malpractice liability have further incentivized physicians, particularly in the U.S., to keep current with genomic medicine applications (26). Everyone from medical students to medical educators recognizes the importance of receiving training in genomic medicine, yet few believe that it is adequately covered in medical curricula at present (27–29).

While there has been some focus on better utilizing certified genetics professionals (e.g. genetic counselors, genetic nurses, medical geneticists) in an educational role (30), given the shortage of these specialized health care providers (31–33), more and more people are calling for physicians—across all education and training levels—to be provided with resources and support to feel confident practicing genomic medicine. Physicians need the right resources to enable development of an adequate knowledge base, the requisite skills, and access to additional learning resources that might include training in how to communicate about complex genomic data with patients (13). Reviews of genomic medicine education have been conducted, but have either been restricted to education initiatives in medical schools exclusively (34,35), or were conducted prior to the past 3 years (36). Given the fast-paced changes in genomic medicine, we have conducted an updated review of this landscape, including the full spectrum of medical education and training levels (see Table 1 for a list of initiatives by medical training level; see Table 2 for a list of initiatives by educational approach). These initiatives have either been proposed or are already implemented and represent different approaches to prepare current and future providers to be well-versed in genomic medicine.

Current Standards in Genomic Medicine Education

Several entities have set the precedent for genomic medicine education standards, as well as the kinds of genomics-related skills and knowledge for which physicians should strive. One of the main guiding frameworks adopted for genomic medicine in the U.S. has been the Accreditation Council for Graduate Medical Education's (ACGME) six core competencies: (i) patient care, (ii) medical knowledge, (iii) practice-based learning and improvement, (iv) professionalism, (v) interpersonal skills and communication and (vi) systems-based practice (37). Both the Association of Professors of Human and Medical Genetics (APHMG) (37) and the Association of American Medical Colleges (AAMC) (38) have adopted iterations of these competencies in order to structure genomics-related learning objectives. Examples of such skills and knowledge include describing the principles, uses and limitations of genetic testing technologies, recognizing the implications of genetic testing and their impact on patients and families, and recognizing the fast pace of advancements in genomic medicine which require continuous learning (37,38). Many medical genetic course directors cite using these guidelines to shape curriculum content and evaluation (29).

In 2013, the Inter-Society Coordinating Committee for Physician Education in Genomics (ISCC) formed in an effort to improve physician education in genomics across multiple training levels by creating a flexible framework that could fit the needs of various professional organizations and medical specialties (39). Most recently, ISCC has focused on five entrustable professional activities [or tasks that can be entrusted to a recent medical school graduate to complete unsupervised (40)], including obtaining a family history, appropriately ordering genomic testing, prescribing treatment based on genomic results and understanding somatic genomics and microbial genomics information (35,39). According to the ISCC's success markers, we will know that genomic medicine education is successful when there are noticeable increases in genomic medicine use by physicians as well as genomic medicine content on certification examinations and during education and training (41). Medical education and accreditation entities will help bolster genomic medicine education by providing incentives to make genomic medicine education a strategic priority (42).

Educational Programs and Resources in Genomics and Big Data

Over the last decade, medical institutions have been considering ways to incorporate innovative genomic medicine education strategies (e.g. personal genome sequencing) into medical education (43). In 2011, Stanford University was the first in the U.S. to successfully integrate such a strategy (44), and this program is described in more detail below. Since then, genomic medicine education and training initiatives have surfaced across the spectrum of physician training to help bridge the gap in genomic medicine preparedness. Although the approaches are diverse, they stem from the notion that physicians of the 21st century must be proficient in genomic medicine applications given their growing role as practitioners of precision medicine (36,45). Given that genomics is an evolving field, there is recognition that genomic medicine training will be an ongoing, career-long learning process (13,46,47).

Immersive and experiential learning

Experiential genomic medicine learning approaches allow learners themselves to participate in genetic testing. Personal genome sequencing (34,48,49) and personal pharmacogenomics testing (50,51) represent two such experiential learning approaches that have been adopted by Stanford University School of Medicine (34), Icahn School of Medicine at Mount Sinai (ISMMS) (34,48,49,51), and the University of Maryland School of Medicine (UMSOM) (50). Stanford and ISMMS introduced personal genotype testing or whole genome sequencing into introductory and advanced genetics courses (34,48,49). ISMMS similarly introduced personal pharmacogenomics testing to further train students to interpret pharmacogenomics results (51). The ISMMS advanced genomics course has since been adapted for physicians, nurses, and genetic counselors, as well as modified to a workshop format for medical students (52). UMSOM opted to utilize personal pharmacogenomics testing in first-year undergraduate medical education (50). In their second year, UMSOM students continue to work with their

Table 1. Genomic medicine education and training initiatives by medical training level

Training level	Program/Initiative
Undergraduate medical education	
• Personal genome sequencing	Icahn School of Medicine at Mount Sinai (34,48,49) Stanford University School of Medicine (34)
• Personal pharmacogenomics testing	University of Maryland School of Medicine (50) Icahn School of Medicine at Mount Sinai (51)
• Cadaver exome sequencing	Temple University's Lewis Katz School of Medicine (34,53,54)
• Genomic medicine ethics case series	Boston University School of Medicine (60)
• Reflective writing	Boston University School of Medicine (59)
• Simulation based learning	University of Copenhagen, Denmark (56)
• Role-playing	Third Military Medical University, China (57)
Graduate medical education	
• One-time intervention delivery of genetics-related content	University of Toronto, Canada (66)
• Conference workshops	Training Residents in Genomics Working Groups through Program Directors Section of Association of Pathology Chairs (55)
• Didactic course, plus lab rotation	Department of Dermatology, University of Connecticut (62)
• Cross-specialty training	Harvard Medical School Genetics Training Program (45) University of Texas Medical School at Houston (63) Division of Cardiovascular Medicine, Brigham and Women's Hospital, Brigham Genomic Medicine (61)
Continuing medical education	
• Resource website	Electronic Medical Records and Genomics Network (14,46) *JAMA Insights: Genomics and Precision Health* (14) The Genetics/Genomics Competency Center Education Resource (70) Genomics England Programme (76)
• In-person training sessions	Icahn School of Medicine at Mount Sinai (46) Electronic Medical Records and Genomics Network (46) Medicine's Future: Genomics for Practicing Doctors, El Camino Hospital, Mountain View, CA (64)
• Genomic education portal	National Human Genome Research Institute (46) Global Genetics and Genomics Community (17,71) Genomics England Programme (76)
• Interprofessional education (IPE)	Institute of Medicine Roundtable on Translating Genomics-Based Research for Health(26)
• Point-of-care tool integrated in EMR to support decision-making	Physician focus group feedback from team practices with EMR in Alberta and Ontario, Canada (11) Electronic Medical Records and Genomics Network (46) The Clinical Genome Resource (72,73)
• Physician buddy system	Physician focus group feedback from team practices with EMR in Alberta and Ontario, Canada (11)
• Push emails	*Gene Messenger* through the College of Family Physicians of Canada (65) Electronic Medical Records and Genomics Network (46)
• Guide for physicians to assess learning needs, genomic medicine webinars	College of American Pathologists (69)
• Board game	Genomics England Programme (76)
• Online course	*Genomic and Precision Medicine* Coursera course from University of California San Francisco (68) Genomics England Programme (76)

genetic results and use them to identify best treatment options (52).

These experiential approaches raise important ethical issues (43). For instance, there is a question of whether the academic medical institution should provide students with informational, psychological or financial support for additional follow-up (48), as well as concerns related to interactions between instructors and students regarding students' health-related results. Concerns with decision conflict about participating in a personal sequencing program led ISMMS to require students enrolled in the advanced genomics course to attend a 2-day, 15-h prerequisite workshop, which provided information to help students make informed decisions about whether to undergo personal genome sequencing (49). Moreover, post-sequencing assessments, following students' completion of the course, showed that most students had low levels of decision regret and distress (49) about choosing to undergo sequencing. Rather than using personal genome sequencing, Temple University's Lewis Katz School of Medicine, recently initiated a program that utilizes cadaver exome sequencing (34,53,54). Cadaver exome sequencing is integrated into the first-year anatomy course to help students become familiar with genetics without the need to implement a separate course (54). This approach has sparked ethical questions for

Table 2. Genomic medicine education and training initiatives by educational approach

Education/training approach	Program/Initiative
Immersive and experiential learning	
• Personal genome sequencing	Icahn School of Medicine at Mount Sinai (34,48,49) Stanford University School of Medicine (34)
• Personal pharmacogenomics testing	University of Maryland School of Medicine (50) Icahn School of Medicine at Mount Sinai (51)
• Cadaver exome sequencing	Temple University's Lewis Katz School of Medicine (34,53,54)
• Conference workshops	Training Resident in Genomics Working Groups through Program Directors Section of Association of Pathology Chairs (55)
• Simulation based learning	University of Copenhagen, Denmark (56)
• Role-playing	Third Military Medical University, China (57)
• Board game	Genomics England Programme (76)
Interdisciplinary and interprofessional approaches	
• Interprofessional education (IPE)	Institute of Medicine Roundtable on Translating Genomics-Based Research for Health (26)
• Genomic medicine ethics case series	Boston University School of Medicine (60)
• Reflective writing	Boston University School of Medicine (59)
• Cross-specialty training	Harvard Medical School Genetics Training Program (45) University of Texas Medical School at Houston (63) Division of Cardiovascular Medicine, Brigham and Women's Hospital, Brigham Genomic Medicine (61)
• Physician buddy system	Physician focus group feedback from team practices with EMR in Alberta and Ontario, Canada (11)
• Conference workshops	Training Residents in Genomics Working Groups through Program Directors Section of Association of Pathology Chairs (55)
• Didactic course, plus lab rotation	Department of Dermatology, University of Connecticut (62)
• In-person training sessions	Icahn School of Medicine at Mount Sinai (46) Electronic Medical Records and Genomics Network (46) Medicine's Future: Genomics for Practicing Doctors, El Camino Hospital, Mountain View, CA (64)
Electronic-based and web-based resources	
• Push emails	*Gene Messenger* through the College of Family Physicians of Canada (65) Electronic Medical Records and Genomics Network (46)
• Guide for physicians to assess learning needs, genomic medicine webinars	College of American Pathologists (69)
• Genomic education portal	National Human Genome Research Institute (46) Global Genetics and Genomics Community (17,71) Genomics England Programme (76)
• Point-of-care tool integrated in EMR to support decision-making	Physician focus group feedback from team practices with EMR in Alberta and Ontario, Canada (11) Electronic Medical Records and Genomics Network (46) The Clinical Genome Resource (72,73)
• One-time intervention delivery of genetics-related content	University of Toronto, Canada (66)
• Online course	*Genomic and Precision Medicine* Coursera course from University of California San Francisco (68) Genomics England Programme (76)
• Resource website	Electronic Medical Records and Genomics Network (46) *JAMA Insights: Genomics and Precision Health* (14) The Genetics/Genomics Competency Center Education Resource (70) Genomics England Programme (76)

students and instructors of whether using cadaver DNA should be protected under human subjects' research and whether the donor's living relatives should participate in the consent process as well as receive pertinent health information from sequencing (34,53,54).

Immersive learning approaches give learners the opportunity to delve into genomic medicine material and pick up key skills and strategies in a modular fashion. Using national conferences and workshops as immersive learning platforms for genomic medicine training has had some utility (55). One novel initiative has been the creation of a one-day team-based genomic pathology workshop for medical residents with experience in molecular pathology (55). Workshop attendees prepare ahead of time by completing pre-selected genomics readings and comprehension questions (55), and the workshop itself consists of expert lectures and hands-on activities (55). The modules used single gene testing, prognostic gene panel testing, cancer gene panels, and whole exome sequencing, and are tied together by a single clinical narrative of a patient with breast cancer (55).

The University of Copenhagen in Denmark has adopted a virtual, simulation based learning approach to teach students concepts and skills in medical genetics (56). Students access virtual patients and interact with a case-based laboratory simulation (56). After choosing and performing laboratory and genetic tests, students are tasked with communicating the results (56). The Third Military Medical University in Chongqing, China has adopted role-playing to help medical students apply knowledge, practice communication skills, and gain interest in genetics (57). Students work in groups on assigned case scenarios over a 2-week period with the help of a tutor (e.g. lecturer, clinical doctor) and take turns in the roles of patient, relative or clinician (57). Each group then performs for the class and participates in a post-role play discussion.

Interdisciplinary and interprofessional approaches

Interdisciplinary and interprofessional genomic medicine education approaches provide opportunities for medical students, other trainees, and practicing physicians to work with health professionals outside of their own disciplines (11,26). Two interdisciplinary initiatives for medical students at Boston University leverage narrative medicine (58) and critical thinking in ethical and social issues in genomics. In the first initiative, first-year students participate in reflective writing exercises tied to a series of patient speakers who have personally undergone genome sequencing (59). After listening to the patients' stories, students are tasked with writing to an assigned prompt and reflecting on the ways patients are impacted by genome sequencing (59). In the second initiative, first-year medical students have access to an ethics case series on genomics topics (e.g. direct-to-consumer, patient privacy, secondary findings) (60), and receive early exposure to the ethical implications associated with genomic medicine (60). Furthermore, this ethics case series was developed such that it can be adapted to meet the needs of trainees and practicing physicians, as well as fit within various forms of curriculum (i.e. traditional or integrated), pedagogical approaches, and educational settings (i.e. lectures, small group discussions) (60).

Several residency and fellowship training programs have adopted interdisciplinary training approaches as well. For instance, the cardiovascular fellowship training program at Brigham and Women's Hospital has proposed a new pilot program for cardiology fellows to work collaboratively with researchers to learn about sequence alignment, variant identification and variant annotation, as well as with genetic counselors regarding ethical and social issues in genomic medicine (61). Residents and fellows in the Harvard Medical School (HMS) Genetics Training Program help lead one-on-one training sessions and provide lectures to trainees in other specialties (e.g. cardiology, neurology) to introduce a basic foundation of genomic medicine while teaching skills to translate genomic results into clinical care (45). Other initiatives include hour-long pharmacogenomic training sessions for internal medicine residents and attending physicians (46), as well as trainee rotations through molecular diagnostic, clinical molecular pathology and cytogenetics labs. In the latter, trainees gain laboratory experience while learning from molecular genetics fellows and laboratory staff (45,62). At the University of Texas Medical School at Houston, residents in pediatrics, child neurology and the combined medicine-pediatrics program complete a 2-week medical genetics rotation where they learn from trained genetics professionals about ways to evaluate patients with potential genetic conditions (63).

Practicing physicians at El Camino Hospital in Mountain View, California have access to an educational series of monthly modules called *Medicine's Future: Genomics for Practicing Doctors* (64). Community-based providers across different specialties (e.g. internal medicine, family medicine, obstetrics and gynecology) participate in 2-h interdisciplinary modules across 10 months. These are led by a clinical geneticist who facilitates discussion and review of interactive cases that draw on narrative medicine and collaborative learning (64). Attendees also view videos of patients with genetic conditions and listen to patients' descriptions of their experiences working with health care providers in this realm (64).

Electronic-based and web-based resources

Genomic medicine educational initiatives have also embraced electronic- and web-based methods for disseminating pertinent information. For instance, disseminating novel genomic medicine information via 'push' emails has been one well-received approach for practicing physicians (46,65). *Gene Messenger*, a 'push' email initiative within Canada, has been used to send bimonthly, short, evidence-based emails with summaries of trending genomics topics (e.g. new gene-disease associations). In conjunction with the new information, physicians complete an online questionnaire that serves as a reflection and evaluation of ways the new information could be envisioned as being useful in clinical practice. Not only have Canadian physicians found *Gene Messenger* to be a helpful resource, but also *Gene Messenger* is low-cost and an effective way to widely disseminate novel genomic information (65). Given that genomic medicine continues to evolve quickly, an email 'push' initiative is one promising approach to provide physicians with just-in-time information. Furthermore, the creators of *Gene Messenger* have developed other iterations called *GEC-KO on the run* and *GEC-KO Messengers*, brief email and more detailed email versions, respectively, as well as launched a web-site, http://www.geneticseducation.ca (65).

Web-based lecture modules may also be a promising intervention delivery model to teach residents about core components of genomic medicine such as taking family histories, assessing risk for hereditary cancers, offering appropriate referral for genetic counseling, and understanding ethical and social issues topics (66). For instance, the University of California, San Francisco has developed an online course, called *Genomic and Precision Medicine*, to introduce a breadth of relevant genetics topics (e.g. family history, pharmacogenomics tests) and help educate physicians to be knowledgeable users of genomic medicine (67,68). One genomics curriculum workgroup from the College of American Pathologists (CAP) has uploaded webinars designed for practicing physicians on the professional society's www.cap.org website; these cover key subject areas in genomic medicine including basic genetics and genomics principles, ethical and social issues topics, sample acquisition, quality assurance and validation, regulatory and compliance, testing and interpretation, reporting, and patient management (69). Similarly, the National Human Genome Research Institute has created a genomic education portal for continuing education and training (46).

The *Journal of the American Medical Association* (*JAMA*) has created JAMA Insights: Genomics and Precision Health, an online resource with curated content intended to educate physicians

in personalized medicine topics (14). The Genetics/Genomics Competency Center (G2C2) Education Resource, www.genomicseducation.net, is a genomic education resource repository developed by the Global Educational Products Working Group of ISCC (39,70). Although originally developed for nurses and physician assistants, it has since been expanded in an effort to meet the perceived needs of physicians (70). G2C2's companion website, Global Genetics and Genomics Community (G3C), www.g-3-c.org, hosts a free, online series of interactive cases with patient scenarios that integrate genetics and genomics (17,71). Users can choose cases with categories ranging from diseases (e.g. Lynch syndrome), patient types (e.g. child, adult), and genetic test types (e.g. whole genome sequencing, direct-to-consumer), as well as case difficulty level (i.e. basic, intermediate, advanced) (71). The series helps physicians assess their level of genomics competency and includes commentary from genomics experts (71).

Physicians have expressed interest in integrating genomic and pharmacogenomic information and just-in-time resources into the electronic medical record (EMR) (11,46). Though promising, this approach would require continuously updating content to ensure physicians are receiving accurate information (46). Nevertheless, The Clinical Genome Resource (ClinGen), a centralized resource funded by the National Institutes of Health focused on improving understanding of genomics in research and clinical practice (72,73), has created an electronic health record (EHR) workgroup. This group is responsible for envisioning a sustainable, accessible, and comprehensive integration of genomic medicine information into the EHR to aid practitioners (73). Overall, electronic-based and web-based resources offer promising means of acquiring genomic medicine education in a low-cost and widely accessible manner.

Education Programs Initiated but With Unclear Outcomes

In response to the implementation of continuing education programs designed to train non-genetics health professionals in genetics- and genomics-related skills and competencies, the authors of one systematic review aimed to characterize these education programs and assess the methodological quality of program evaluation studies (74). Using genetics- and genomics-related terms, the authors searched from 1990, the start year of the Human Genome Project, through June 2016. In summary, across 44 articles, the authors found few theory-driven curricula, a lack of rigorous study designs to evaluate the effect of the programs, and lack of evidence presented on the reliability and validity of the outcome measures used (74). Although most of the studies that utilized pre/post study designs did conclude that the respective education programs had positive outcomes at follow-up, the vast majority of the studies collected follow-up information immediately after the program was administered (74), and thus, it is difficult to assess the impact of such programs on physicians' longer-term knowledge on the subject, as well as their longitudinal practice-related behaviors.

Several programs mentioned in this article have included evaluations of the education initiatives using different types of assessments. For example, in early 2018, ISMMS published findings on the impact of incorporating personal genome sequencing on educational outcomes. The study was based on data from three course years (i.e. 2013–2015) and findings suggested that personal sequencing improved motivation and engagement among participating students (49). These results are also consistent with previous findings from the Stanford University program that suggested increased educational value associated with the use of personal sequencing in medical education (75). In addition, students involved in the simulation based learning at the University of Copenhagen (56) as well as role-playing at the Third Military Medical University in Chongqing, China (57) reported improved understanding, motivation, and confidence in using medical genetics. Trainees who completed the 2-week medical genetics rotation at the University of Texas Medical School at Houston reported positive interprofessional encounters with the genetics staff (63), and physicians at El Camino Hospital in Mountain View, California felt increased confidence in genomic medicine clinical skills (64). Future studies may wish to compare educational approaches to determine which ones produce the best outcomes. Furthermore, program evaluations and assessments may benefit from the development of reliable and valid measures to evaluate genomic medicine knowledge, skills, and communication.

Genomics England

We also reviewed the Genomics England Programme (GEP) within Genomics England, a national genomic medicine initiative in the UK, and found several education and training tools described on their website (76). One particularly innovative tool was a genomics board game, 'The Genomics Game', originally made for nurses but intended for any healthcare provider who wants more exposure to genomics-related topics (76). Other approaches include online courses, an education portal, and a resource website. In addition, funding is available through a centralized application process for the provision of genomics classes at universities in the UK (76). We note that these descriptions of the GEP were not yet available via the published literature, and look forward to further dissemination of these tools and published reports on any outcomes.

Other Considerations for Genomic Education

The rapid pace of discoveries in genomics requires that genomic medicine education initiatives are designed to incorporate continuously updated, novel information (13). While new information adaptability is one important consideration, communication of genomic information is equally as critical; for instance, an integrated 360° feedback communication approach (77) may be one promising way to teach genomics communication skills (78). Training in narrative medicine may also be beneficial to help physicians improve attention and listening skills (58) which are critical for any patient encounter but may be especially useful in complex cases involving genomic information. Medical education curricula would also benefit from clearer learning objectives for genomics, precise assessment methods, and clear objective metrics (79). Discussions of the reliability and quality of genomic data are also important for integration into clinical care (24,80), as are the impacts of big data on physician workflow (24,81). Physicians express concern about burden on clinical staff as genomic and other forms of big data require additional time to understand, interpret and explain (24,82). Given the many time demands on physicians, convenience is a high priority when incorporating new technologies into clinical care and the physician-patient relationship (83). We also note important limitations of this article, including that our review focused on initiatives mentioned in the published literature. Future work that systematically assesses genomic medicine

programs across all medical schools, as one example, could be useful in order to better understand the full landscape of genomic medicine education across a known sampling frame. Another limitation is our focus on U.S.-based programs given their over-representation in the literature at present.

Conclusions and Future Directions

We reviewed the literature in genomic medicine education and training at the undergraduate, graduate, and continuing medical education levels, largely within the U.S., with a focus on articles published between June 2015 and January 2018. We found evidence of innovative and creative genomic education initiatives and ideas to increase physician knowledge of and readiness for genomic medicine applications. Three educational approach themes emerged—immersive and experiential learning; interdisciplinary and interprofessional education; and electronic- and web-based approaches. Electronic- and web-based resources (e.g. 'push' emails) specifically may provide promising solutions to disseminate information widely, quickly, and in a low-cost manner. Furthermore, systematic evaluations and assessments of educational interventions should ideally accompany all genomic education initiatives in order to build an evidence-base for the optimal ways to educate practicing physicians, residents, fellows, and medical students (74). Lastly, interprofessional and interdisciplinary approaches mirror collaboration trends in clinical care, and from our review, we see evidence of the utility of this approach in training physicians in genomic medicine by leveraging the expertise of, e.g. genetics specialists. Overall, it is the aim of this review to provide information that will ideally be useful to institutional leaders, instructors, course directors, program administrators, and medical education experts who will continue to participate in designing and expanding access to genomic medicine education programs for physicians.

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