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Radiology, Mobile Devices, and Internet of Things (IoT)

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Abstract

Radiology by its nature is intricately connected to the Internet and is at the forefront of technology in medicine. The past few years have seen a dramatic rise in Internet-based technology in healthcare, with imaging as a core application. Numerous Internet-based applications and technologies have made forays into medicine, and for radiology it is more seamless than in other clinical specialties. Many applications in the practice of radiology are Internet based and more applications are being added every day. Introduction of mobile devices and their integration into imaging workflow has reinforced the role played by the Internet in radiology. Due to the rapid proliferation of wearable devices and smartphones, IoT-enabled technology is evolving healthcare from conventional hub-based systems to more personalized healthcare systems. This article briefly discusses how the IoT plays a useful role in daily imaging workflow and current and potential future applications, how mobile devices can be integrated into radiology workflows, and the impact of the IoT on resident and medical student education, research, and patient engagement in radiology.

Keywords Internet of things · IoT-based radiology · Mobile applications radiology

Introduction

The Internet of Things (IoT) is rapidly extending Internet connectivity into a plethora of devices and objects used in everyday activities and tasks. It offers a distributed environment containing a vast number of applications such as smart wearables, smart homes, smart mobility, and smart cities. In healthcare, the IoT is driving a revolution to design effective and efficient healthcare delivery by forming a seamless platform for communication between various segments of the healthcare environment, enabling digital support at each step. Embracing digital solutions to support the evolution and transformation of health services is essential [1, 2]. Imaging workflow entails seamless integration of data at the level of the patient, scheduling, billing, imaging data acquisition, storage and transfer, and physician for optimal productivity. Well-developed connections between systems at each level of imaging workflow, facilitated by the Internet, form the backbone of radiology and are usually manifested by a strong system-wide infrastructure. Information technology (IT) in radiology

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is constantly evolving, and advances allow for improvements in workflow, quality control, efficiency, and patient care [3].

IoT-enabled mobile devices have revolutionized communication. Mobile devices have the processing power to display, manipulate, transmit, and share large imaging data sets. These capabilities have many implications for radiology, from advances in teleradiology and consultation to more efficient workflow, patient care, and education [4–6]. Many mobile apps also collect information about the user via the mobile device or wearable device. Mobile medical apps, as defined by the US Food and Drug Administration (FDA), meet the definition of a medical device and are an accessory to a regulated medical device or transform a mobile platform into a regulated medical device [7].

This paper discusses the commonly used mobile applications at various levels in radiology and talks about the existing IoT-based applications. Since security is an inherent concern with Internet-related technology or digital data, the paper then discusses security concerns in radiology and existing technologies to address it.

Applications for Patient Care and Radiology Workflow

This section summarizes various applications in use and under research that facilitate enhanced patient care by improving imaging workflow.

Image Sharing

An emerging use of the Internet to improve patient care is the use of Internet-based networks for electronic sharing of imaging studies. Studies have documented the use of iPad (Apple Computer, Cupertino, CA) for near-instantaneous transfer of images from the ICU to intensivists and radiologists [8]. Internet-based solutions for sharing medical images, instead of compacts discs, improve efficiency of communication among providers and allow patients to have direct access to their imaging studies and reports. The Image Share Network (ISN) developed by the Radiological Society of North America (RSNA) gives patients direct control of their imaging studies and reports through a secure and HIPAA (Health Insurance Portability and Accountability Act)-compliant cloud-based electronic personal health record that can be shared with providers [3]. Studies on the use and satisfaction of ISN implemented at select institutions showed favorable response among most participants to having direct access to images and reports [9].

Imaging Interpretation and Viewing

Mobile technology offers many applications to improve radiology workflow, including image viewers, remote desktop access, screen sharing, and real-time consultation. DICOM (Digital Imaging and Communications in Medicine) viewing applications give users the ability to view imaging studies remotely, with implications for collaboration, consultation, and faster diagnosis and treatment. With regard to image interpretation, mobile devices have many potential advantages in the context of teleradiology. Following the release of the iPhone and iPad (Apple computer, Cupertino, CA) in the late 2000s, informatics group at the Massachusetts General Hospital developed an in-house application to study performance of these devices in cases which require urgent reads such as telestroke [10], CT head from emergency departments [11], pneumothorax on chest radiographs [12], and chest CT angiograms for pulmonary embolism [13], using PACS as the gold standard. These studies found good agreement between viewing images on the mobile devices and PACS (Picture Archiving and Communications Systems). The system enables preliminary reads remotely thereby enabling faster response. A study performed at the Mayo Clinic incorporated the use of ResolutionMD, a mobile-based teleradiology system developed by Calgary Scientific that enables access to imaging studies on smartphone and tablet devices without the need for storage [14]. Results showed excellent interobserver agreement in the identification of critical findings, corroborating previous studies demonstrating that mobile-based teleradiology systems may be a useful tool for acute imaging assessment. Multiple applications are available, serving as mobile PACS workstations to stream data from imaging studies to mobile devices [15].

ResolutionMD is one of few DICOM viewing applications approved by the FDA for diagnostic use. FDA approval is subject to performance measures including luminance, image resolution, and image noise [16]. Other FDA approved viewing platforms include Fujifilm Synapse Mobility, developed by Fujifilm Medical Systems, as well as Mobile MIM, developed by MIM Software. The latter was the first FDA approved radiology image viewing app, with the limitation that it had to be used only when there was no access to a PACS workstation and users had to "pass" an ambient light and screen luminance quality check in order to view images. Despite FDA approval, these applications should be used with some caution because there is mixed evidence on diagnostic accuracy when using them [16]. In addition, even though mobile devices have some quality control measures integrated into them, they cannot be calibrated in the same way a diagnostic monitor is and cannot be subjected to the same quality assurance procedures that PACS workstations are required to undergo [17].

With regard to image viewing, mobile DICOM applications are becoming popular with clinicians who desire portable access to imaging studies. The applications range from assisting physicians in placing appropriate imaging orders [18], to providing easy access to studies during rounds and in the operating room [4, 19]. These applications have the potential to aid in every step of the imaging workflow, starting from order entry system, image interpretation and generation, and dispersion of report to ordering physician, and have been shown to be effective in this in some institutions [20].

Mobile Imaging Devices

An emerging application of mobile technology in radiology is the smartphone-based ultrasound device. One example is the MobiUs device developed by Monisante, consisting of a handheld ultrasound probe connected to a smartphone with the MobiUS application installed. Images are transferred to the smartphone camera, allowing for easy sharing of images remotely for diagnosis, archival, or consultation. The device is highly portable, is inexpensive, and has accuracy comparable to traditional portable machines. They are especially popular among providers in rural areas and where other technologies are not widely available [21, 22].

Reference and Consultation Applications

The American College of Radiology (ACR) developed a website in 2015 called R-SCAN, the Radiology Support, Communication and Alignment Network™. R-SCAN provides a portal for radiologists and referring providers to connect and collaborate in order to select the most appropriate exam for the patient. The site offers educational resources about when to image patients based on the Choosing Wisely® recommendations as well as the ACR Appropriateness Criteria®. In addition, radiologists and referring providers can meet their annual quality improvement activity credit requirements by completing one R-SCAN project together [23]. Similarly, a reference application called iRefer, developed by The Royal College of Radiologists, provides quick and easy access to guidelines to assist referring providers when ordering imaging studies for a given diagnostic problem based on the best available evidence [21, 24].

Real-time consultation between radiologists is important in the setting of a complicated or difficult case, and applications have been developed to facilitate communication between radiologists. MagicRad is a free clinical tool that enables an imaging study to be uploaded to a computer and shared with a protected online radiology network called Radiolopolis. The images are captured directly from the workstation. The community is alerted to the case and can offer their opinions and recommendations in real time [25].

There are several additional reference applications available that can positively impact radiology workflow and patient care. Radiation Passport developed for the iPhone by Tidal Pool Software provides users with radiation exposure levels and potential risk factors associated with different radiology exams. Average radiation dose values for over 140 exams are included [26].

App developer RADIOLOGiQ, LLC offers many reference apps designed to address recurring “pain points” in radiology workflow. For example, the Management Guide for Incidental Findings on CT and MRI provides a simple clickable algorithm for incidental CT and MRI findings based on the ACR Incidental Findings Committee white papers. The ACR guidelines address commonly encountered findings such as thyroid nodules and cystic pancreatic masses, and the app provides a quick and easy reference for management recommendations. Another popular app, the Atlas of Medical Devices on Chest X-ray, provides a comprehensive collection of the radiographic appearance of medical devices encountered on chest X-rays. The collection is searchable and organized into categories such as cardiac conduction, vascular, airway, and enteric devices [27, 28].

NSF (nephrogenic systemic fibrosis) vs. CIN (contrast-induced nephropathy) is an app developed by Sandro Fenelon offering decision support and protocol guidance to radiologists, referring clinicians, and technologists when imaging patients with renal impairment using contrast. Data for both CIN and NSF are summarized for iodine- and gadolinium-based contrast agents, and the app uses the calculated eGFR (estimated glomerular filtration rate) integrated with a risk estimate generator to provide decision support for screening and protocolling contrast-enhanced exams [29].

For Medical Education

Among the influences of the IoT and mobile devices on radiology, one of the most powerful has been on radiology education. Radiology education for medical students, residents, fellows, technicians, and staff is enhanced by a multitude of new mobile apps, educational websites, social media, and classroom enhancements tools. Technological advances have expanded the spread of radiology knowledge and experience to all forms of learners across the globe. In this section, we will discuss some of these new technological tools and the impact they have had and continue to have on radiology education.

Mobile Apps

With the rise of mobile devices such as tablets and smartphones, there has been an exponential growth in apps for Radiology education [21, 30–34]. Mobile apps are affordable, are accessible on many devices, and can be preloaded onto program-purchased mobile devices [34, 35]. The most common and popular app providers include those from the Apple and Android platforms [21]. Apps used in radiology education include administrative apps, assessment and case presentation apps, and imaging apps [35].

Administrative Apps

Medical school classes, radiology residency programs, and radiology departments benefit from administrative apps that help with file sharing, note-taking, scheduling, communication, assignment submission, and classroom management [35–37]. These apps permit large-sized documents to be uploaded and shared among users on a variety of platforms, including app platforms and any computer with Internet access [37].

Notetaking and word processing apps have revolutionized classrooms throughout education, especially in higher medical education [36, 37]. The sensitive touchscreens on mobile devices allow for natural note-taking with a stylus, in addition to built-in or Bluetooth-linked keyboards [37]. Examples of these apps include Noteshelf, Notability, and Google Keep [35, 37]. Many of these apps now also include handwriting analysis and voice recognition to improve notetaking ability. Evernote and Microsoft OneNote provide a cloud-based note filing system that not only allows notes to be typed, but they have a multimedia component that allows images, weblinks, and video to be saved to the note. Evernote has a built-in web-clipper add-on that allows for snapshots from websites to be taken and added to the notes. A powerful classroom benefit with the Google Docs apps is that they allow for easy collaboration on assignments and projects, with document changes simultaneously tracked and discussed [36].

Scheduling and communication apps facilitate organization within residency programs and healthcare organizations. There are many calendar apps that can facilitate scheduling, including Amion, Google Calendar, iCal, and Any.do. Calendar apps like Google Calendar can provide much more than simple scheduling of activities. Google Calendar allows for multiple event schedules to be created, including call schedules, lecture schedules, and rotation schedules [35]. Many mobile apps have facilitated communication among health professionals. Communication apps not only send text messages, but also pictures and video [35]. GroupMe is an app that can send text messages. Edmondo, iMessage, FaceTime, Google Hangouts, WhatsApp, and Facebook Messenger can send text messages, pictures, or video [35]. While these apps can be an excellent means of communication, the communication is not secure, particularly for patient information. Although not free, apps such as Tiger Connect and Vocera allow for HIPAA-compliant text messaging, picture and video sharing over the secure hospital network. In addition to interpersonal communication apps, there are apps that allow for communication of lectures and conference meetings. These apps allow for audio, video, and screen-sharing communication, including Webex and GoToMeeting [34, 38].

In addition to the administrative apps mentioned above, an important classroom management tool involves the use of audience response and classroom assessment systems. Google Docs has an app called Google Forms that can be used to create question for assessment or even for audience response, with a wide range of possible question types and the possibility for multimedia attachment [36]. Add-ins to Google Forms, such as Flubaroo, can even be attached to allow for assessments to be automatically graded based on the instructor-supplied answer key [36]. Real-time assessment and audience response are also possible through the analysis function in Google Forms. Additional audience response apps include Poll Everywhere, eClicker Presenter, Audience, and TurningPoint [32, 35, 39]. These audience response systems allow for learner engagement and create an almost game-like environment for the learners [39, 40].

Assessment and Case Presentation Apps

The widespread use of mobile apps permits distribution of radiology knowledge across the globe. Radiology questions, images, and teaching modules in mobile apps can be readily created and shared among all types of learners. The best images and examples of radiology cases can be collected and displayed in large, online, image repositories. These apps and online websites pose an advantage and challenge for Radiology education. While a large amount of information is widely available for free or low cost, the learner needs to use discretion to ensure that the information provided is high quality and validated.

For radiology residents studying for qualifying and certification exams, there are applications containing radiology questions and self-assessments [41]. Similarly, early career faculty and fellows preparing for the certifying exam or sub-specialty CAQs utilize question apps. IMAIOS created a question app called QEVLAR [42] that tests qualifying core radiology topics, as well as a separate set of questions specific to the Nuclear Medicine subspecialty certificate (CAQ). Radiology 300 [43] and Radiology Core [44] created apps to test physics review questions. Large image repositories and case-based radiology learning module apps present learners with many cases, far more than can be provided in many institutions. Radiology Assistant [45], created by Radiologists in the Netherlands, provides learners with radiology teaching modules and cases that outline important topics in radiology. A unique aspect to Radiology Assistant is that it teaches learners basic science and physiology principles behind the Radiology findings. Radiopaedia [46] is a large, global online image repository founded by radiologists in New Zealand that promotes case-based learning. Other similar applications that are more subspecialized include MSK Radiology 4 U [47] created by musculoskeletal radiologists that provides learners with 3000 anonymized case studies in musculoskeletal imaging. SonoAccess [48] contains a library of ultrasound videos and documents, and iRefer [49] is an app by the Royal College of Radiologists that provides guidance and evidence for diagnostic radiologists. Lastly, many radiology journals provide learning opportunities through their mobile apps.

Educational Websites

Many of the previously described mobile apps have companion websites that provide administrative support, assessment and case presentation services, and imaging services. Some radiology education programs are only available on the Internet. Unlike the mobile apps, there are many more websites dedicated to radiology education. Like information obtained with mobile apps, learners need to use caution when accessing radiology education online, ensuring that the information comes from valid, reputable sources.

We will focus on radiology education apps with assessment and case presentation functions. StatDx is a large subscription website that functions as a radiology encyclopedia, similar to Radiopaedia. Studies looking at resources used by radiology learners cite StatDx as one of the top electronic resources [35, 50]. StatDx describes many different diagnoses, including their pathophysiology, classic appearances on imaging modalities, differential diagnoses, and references. The makers of StatDx also created a subscription online learning and assessment website, RadPrimer. RadPrimer has a large database of multiple-choice questions to help learners as well as online learning modules. Learning Radiology is another popular website, particularly among medical students learning the basics of radiology [37]. ACR Case in Point is an online, peer-reviewed case presentation website that presents cases with discussions and questions related to the differential diagnosis or pathophysiology. AuntMinnie is a popular website that contains many educational resources, including teaching cases, radiology news, board review, CME (continuing medical education), and conference reports. Yottalook is an interesting search engine that specifically searches medical images. In addition to the QEVLAR questions described above, IMAIOS provides a subscription service called eAnatomy that provides learners with detailed anatomy on representative CT and MRI images. Additional websites with cases, case discussions, and tutorials include Radiology Education, MyPACS Teaching File, MedPix Teaching File, ACR MRI Teaching File, RadQuiz, CT is US, Imaging Consult, Lieberman's eRadiology, Radiology Database, EURORAD, and Brigham Rad Online Teaching Cases [37]. Websites such as ImagingRealm.com (funded by an RSNA grant) have been developed on low bandwidth solutions to provide educational resources to view and download in low-income resource settings [51, 52].

Social Media Radiology Education

In addition to the radiology education websites described above, social media websites are increasingly becoming platforms for radiology education [53, 54]. Social media platforms provide free, widespread access to information. Radiology organizations, academic centers, and radiology training programs are putting up radiology images, case files, and online modules on a wide variety of social media platforms, including Twitter, Facebook, and Instagram [53, 54]. Again, caution must be used to ensure that the information posted on social media sites is reputable.

Twitter allows users to create short messages, composed of no more than 140 characters. Radiology education on this platform typically involves short links to journal abstracts, YouTube videos, or radiology education events. Radiology chats about educational topics or articles can also be initiated [53]. A commonly used radiology education hashtag is #FOAMRad, which stands for “free open-access medical education radiology” [53]. The #FOAMRad hashtag can be found attached to many different radiology education events across the Internet. Dr. Nicholas Koontz from Indiana University developed #IUCOTD to present short YouTube videos (5–12 min) that present radiology cases [55, 56]. #EmoryRadCOTD by Dr. Ryan Peterson and colleagues at Emory presents cases of the day with answers after 24 h, similarly providing universal access to high-quality radiology education.

Facebook, unlike Twitter, allows for longer posts with more opportunities for image and video attachment. Facebook allows up to 60,000 characters and videos up to 45 min [57]. Radiology societies commonly utilize Facebook to promote their society, connect with members, and broadcast during conferences. Radiology education websites like Radiopaedia and Learning Radiology utilize their Facebook pages to present cases and online learning modules. Facebook also has the largest member base of any of the social media platforms, including global users [53]. Instagram has the benefit of being almost entirely image-based. Instagram allows 2200 characters and 60-s videos [53, 57]. The images can have Twitter hashtags attached to them, allowing for searching. Instagram can also be used to create online quizzes for radiology learners [53].

Internet-Based Radiology Education Curricula

With the rise of Internet and mobile education, educators have begun to develop online radiology educational curricula. These curricula are being developed to educate radiology residents, staff, technologists, and medical students. Published curricula include curricula based on mobile apps, websites, audio podcasts, social media teaching platforms, and learning management systems (LMSs) [30, 58–61].

Many residency programs have purchased iPads for their residents as an incentive and an educational tool, and some have also installed specific mobile apps helpful in radiology education. At Beth Israel Deaconess Medical Center, iPads were given to residents as a learning tool with subscriptions to eAnatomy and STATdx [30]. Following institution of the program, Berkowitz et al. found that 86% utilized the iPad daily, with the eAnatomy app used most frequently [30].

At the University of Colorado, Sharpe et al. reported on the implementation of a "Radiology Resident iPad Toolbox" that contained mobile electronic resources for radiology education [34]. The "Toolbox" contained radiology education mobile apps, textbooks, case files, journal access, lecture notes, and lecture videos. Clinical apps were installed, including Amion for scheduling and Citrix Receiver to access the hospital PACS and electronic medical record. Residents reported significantly shifting studying from paper resources to the iPad resources [34].

At the University of California, Riverside School of Medicine, Alexander et al. reported on the development of a unique Internet-based radiology course for 4th year medical students [58]. The faculty developed an online curriculum to teach radiology compared with an in-person radiology curriculum. They wanted to determine if the curricula were equivalent in efficacy, using the Alliance of Medical Student Educators in Radiology (AMSER) test bank as the assessment tool. They found that the AMSER scores for those with the Internet-based curriculum versus the in-person curriculum were not significantly different.

Dartmouth Medical School exposed medical students to an online case-based tool, Case Oriented Radiology Education (CORE), to teach radiology through cases [59]. The cases were published through the CASUS authoring system, which allowed for online text, interactive questions, hyperlinks, and multimedia. Students felt that the CORE cases made good use of their time (84%) and provided appropriate resources for their level of training (86%). They felt that it expanded their radiology knowledge and understanding (88%) [59].

LMSs are e-learning platforms that allow for the development of online radiology education resources [60–62]. In LMSs, the shareable content objects (SCO) such as lectures, videos, and teaching files are accessed in real time by the LMS software to present the content to radiology learners [61]. NeuroRAD is a neuroradiology virtual learning community that uses the Moodle LMS software to present online courses, online lecture, review articles, and cases. PediatricEducation.org is a pediatric radiology case platform that utilizes Manila LMS software to present its cases. Online podcasts and lectures are another mechanism for developing online curricula for radiology education [62, 63]. As previously discussed, Koontz and colleagues developed short, online lectures via Twitter and Youtube [55, 56]. Rowell et al. discuss how to create audio podcasts on educational topics in radiology [62] on their website CTisus.com.

For Research

Perhaps no single technology since the printing press has had a bigger impact on scientific research than the Internet. Medical research involves various personnel including the researchers, who can be physicians and non-physician researchers. Physicians use various medical applications and devices as discussed in the clinical applications and education sessions to gather information. This section focuses on applications available for researchers and mobile applications that are helpful for patients participating in researches or looking for literature.

Other than the obvious benefits of allowing for international collaboration and the electronic dissemination of data and published papers, the Internet has enabled many advances that foster research. The World Wide Web (WWW) specifically has enabled researchers to much more easily search for publications using sites like Pubmed [64]. With the availability of mobile devices, clinicians now have access to a wellspring of information at their fingertips, through their smartphones and tablets [65]. Mobile apps relevant to research include apps for patient care and monitoring; health information for the layperson; communication, education, and data collection; and physician/student reference [66].

For researchers, a multitude of mobile applications exist for searching the literature and organizing references. To aid them, various journals have apps and/or mobile-optimized website for easier access on phones and tablets; however, these are usually through subscription, personal, or institutional [67]. Open Access has revolutionized the publishing world, among them PLOS is a leading organization campaigning for free and open access [68]. PLOS applies the Creative Commons Attribution (CC BY) license to their publications for facilitating Open Access resources which are free, immediately accessible with unrestricted reuse of original works. Under this license, authors agree to make articles legally available for reuse, without permission or fees, if the author and original source are properly cited. Additionally, the journal platform that PLOS uses to publish research articles is Open Access [69–71]. There are many other organizations, such as SPARC (the Scholarly Publishing and Academic Resources Institute) and the Open Society Foundations that work tirelessly for progress in Open Access [72, 73]. These societies and organizations are usually funded through donations and fundraisers. The content is currently very limited, but this is changing rapidly. Availability of such technology is most useful while performing meta-analysis or large systematic reviews of literature [73].

Several mobile applications exist for PubMed search, National Library of Medicine access, research reference organization (i.e., EndNote), and most journals have apps and/or mobile-optimized website for easier access on phones and tablets. Some medical literature search apps include the following: PubSearch, PubMed on Tap, Medscape, MEDLINE Database on Tap (MD on Tap or MDoT), Docphin, Docwise, Read by QxMD, askMEDLINE, PICO, and Disease Associations [74]. These iOS-enabled applications can be free or by subscription only. A recent survey of healthcare professionals and students found that more than one third used mobile devices to access medical journal websites (60%) or medical news online (74%) [75]. Another study showed that browsing was most popular activity among healthcare professional (HCPs), with 98% using their desktops/laptops, 63% using tablets, and 56% using smartphones [76]. It was found that among smartphone users in health care settings, physicians spend an average of 3 h per week watching web videos for professional purposes on desktops/laptops (67%), tablets (29%), and smartphones (13%); the most frequently viewed content (55%) was CME [76].

There are a wide variety of mobile apps available for healthcare professionals, and the *Journal of Digital Imaging* regularly publishes reviews of those relevant to radiology [77]. Several drug reference applications are commonly used by physicians to access drug-related information [74]. Many institutions have radiology research sites highlighting their faculty's or institution's achievements. This enables review of that institution at the time of application by researchers, fellows, residents, medical students, and even faculty. The free app MD on Tap is provided by the National Library of Medicine to help HCPs using personal digital assistants (PDAs) access medical information at the point of care through three search engines: PubMed, Essie, and Google [74].

The Internet has also enabled patients and research subjects to become more active participants in clinical trials. Websites can allow patients and families, researchers, and study record managers to search for and get involved in applicable clinical trials [78]. Places like the Mayo Clinic have links to "finding clinical trials" that patients can use to enroll [79]. Through clinical studies, researchers can better understand how to diagnose, treat, and prevent diseases or conditions. Outside of the traditional large academic institutions conducting research, large private radiology practices are joining with academic centers to improve the peer review process [80] and are beginning to form research collaborations which communicate primarily over the Internet [81]. With advances such as machine learning within radiology where large volumes of data may need to be sent around the world, the Internet will only become more important to the clinical application of radiology and radiology research.

For Patient Engagement

Patient Portals

Online patient portals are websites linked to EMRs that allow patients to directly access, view, and download their medical information. Per Meaningful Use incentives, patient portals offer the ability for patients to "(1) view a clinical summary to the patient after each visit, (2) secure messaging (SM) between patient and provider, (3) ability to view, download, and transmit personal health record data, (4) patient specific education, (5) patient reminders for preventative services, and (6) medication reconciliation" [82].

Patient portals were originally introduced in the 1990s but did not see widespread adoption until the mid to late 2000s with the passage of the Health Information Technology for Economic and Clinical Health (HITECH) Act of 2009 [83]. Between 2013 and 2015, there was a sevenfold increase in the number of US hospitals that offered patients access to online portals. In fact, in 2016–2017, over 90% of US hospitals offered the ability to view medical records online, and 68% allowed patients to send messages to their healthcare providers [84].

The major drawback of patient portals is that adoption rates are only around 50% according to a recent meta-analysis [85]. Furthermore, patient factors such as age, race, sex, and income of patients all influence adoption rates [86].

When authors from a large academic health center analyzed over 50,000 patient-initiated messages in their online patient portal, they found that approximately 3% of all patient-initiated messages through their online patient portal were related to radiology studies [87]. However, most healthcare systems and radiology practices do not currently enable the capability of patients to send messages to radiologists, despite the widespread patient accessibility of radiologists' reports on patient portals.

Mobile Devices

By virtue of having larger screens (often about 10 in. diagonally), tablets are more appropriate for image display and manipulation than smartphones. They are more portable than laptop computers, and tablets have been postulated to be ideally suited to radiologists reviewing images with patients, for example in the emergency department [88]. Providers have long leveraged mobile devices as a reminder tool. Sending automated text messages to remind patients of upcoming interventional procedures [89] and diagnostic examinations [90] as well as associated requirements such as bowel preparation [91] has been shown to improve patient adherence. In a prospective, randomized controlled study in Shaanxi, China, that enrolled patients who have undergone endoscopic retrograde cholangiopancreatography (ERCP) and implantation with plastic or covered metal stents, those in the intervention group that received monthly text message reminders of their stent removal/exchange appointments had a significantly higher rate of adherence (18/23, 78%) compared to those in the control group that did not receive those reminders (10/25, 40%) [92].

RADiDOC is an iOS app developed by radiologists at UCLA. Designed for use by patients, clinicians, and radiologists, RADiDOC provides radiation dose estimates for imaging procedures, cumulative patient dose tracking, and education about radiation dose concepts. A patient who has questions or concerns about radiation exposure can look up an imaging study and learn about the associated dose and how it compares to other forms of radiation exposure such as background dose or exposure during a flight. RADiDOC is currently available for iOS only. [93].

RadiologyInfo.org is a useful website providing patient education on how various X-ray, CT, MRI, ultrasound, radiation therapy, and other procedures are performed. It also addresses what patients may experience and how to prepare for the exams [94]. The website is jointly developed and sponsored by the RSNA and the ACR. In 2018, the site launched a new section called RadInfo 4 Kids, designed specifically for children to help them prepare for imaging exams and procedures. RadInfo 4 Kids contains videos, stories, and games created by children for children to help make them more comfortable undergoing radiologic exams [94]. Mobile-optimized interfaces for patient Web portals with features such as push notifications and scheduling a consultation session with a radiologist may offer more immediate interactions between radiology services and patients.

IoT-Enabled Wearables

Implantable medical devices such as cardiac loop recorders, electronic pain pumps, insulin pumps, and the like have become a commonplace in medicine. Up until now, medical devices such as these have required a healthcare provider to prescribe them. However, with the introduction of the 4th generation of the Apple Watch, consumer-grade wearable medical devices have now become mainstream. The device was cleared by the Food and Drug Administration to allow for electrocardiogram monitoring and detection of irregular rhythms [95]. To date, wearables, sensors, and implantable devices are clearly impacting Telehealth and remote monitoring applications, but how and if they will impact radiology is yet to be seen. While very few consumer-grade devices that allow for medical imaging exist (see for example Breastlight https://www.breastlight.com/ [96]), more will likely be developed given the current trends of the consumer market. Medical professionals and specifically radiologists should be prepared for such a possibility.

Internet and Security

(a) Legal and security considerations in Internet-based radiology education

Internet-based radiology education resources allow for widespread dissemination of radiology information. Along with the benefits of online education, there are challenges, including resource validity and potential legal problems.

As previously mentioned, a challenge with multiple sources of readily available radiology information is determining whether the sources of information are valid. Journal articles generally maintain rigorous peer review standards to validate the educational material. Many resources, such as Radiopaedia, STATdx, RadPrimer, IMAIOS, and other online resources, similarly employ peer review to ensure validity. There are numerous resources that do not demonstrate a similar peer review process and should be viewed with skepticism. The responsibility for determining validity lies with the individual radiology learner, particularly as many of the radiology-associated apps do not acknowledge professional or societal input [32]. Knowledge of the last time the application or website was updated is crucial to assess the validity of provided information and trends.

Radiology education employs the use of patient images, which necessitates patient privacy protection [32]. There are an increasing number of lawsuits based on loss of patient privacy when images and other data that have not been anonymized are posted. The risk to patient privacy is increased due to the mobility and widespread use of mobile devices that can be stolen or lost. It is important to ensure that all patient-specific information is removed from images and data prior to posting the images online.

A further legal implication is the protection of intellectual property. Bedoya et al. demonstrated that learners were less interested in concerns about intellectual property when lectures are recorded [50]. The widespread nature of the Internet can promote equalization in radiology education across the globe, but it can also be a challenge when intellectual property is unlawfully distributed to the detriment of the resource creators. Some reluctance to putting image collections and teaching materials online is the concern that the work may be appropriated or used without attribution or (in some cases) compensation.

(b) Legal and security considerations in Internet-based radiology data

Technological advancements have their benefits, but not without the risk of loss of security and decreased accuracy. To maintain standards and monitor the quality of applied technology in medicine, those used for diagnoses, treatment, and patient care have to cross several hurdles regulated by governing authorities such as FDA and various other organizations. Several milestones include regulatory approval, early clinical evaluation, payer reimbursement, and broader marketplace adoption need to be met prior to successful implementation [16]. These steps mandate active demonstration of clinical value during each phase of translation [16].

Data security is a must when developing mobile apps for patient engagement, particularly apps that transmit personal health information to the user. Securing personally identifiable healthcare information is a mandate of HIPAA. The HITECH Act extends HIPAA liability to business associates (which covers entities that handle protected health information, including vendors of electronic healthcare records and imaging data) and imposes additional requirements such as data breach notifications and periodic audits by the Department of Health and Human Services [97]. HITECH Act provided for financial incentives to healthcare providers to support patient access to their medical records. Given that patients' personal mobile devices may be configured with variable degrees of security and may be sometimes be connected to unencrypted networks, extra care should be exercised to develop apps that secure personally identifiable information against device loss, theft, and hacking.

The FDA and AAPM recently released a new report on mobile device viewing guidelines [98]. Security networks have to be implemented at each step of user interface with the Internet platform in radiology as well as the level of inter-device communication. Familiarizing radiology managers and end-users with security measures that prevent unauthorized use of the device, including passcode policies, is an important step. Procedures for protection of patient data in compliance with Health Insurance Portability and Accountability Act and US Federal Information Processing Standards should be adopted infrastructure wide.

Device security measures for data protection include local data encryption, hardware encryption, and wireless network security protocols, including wired equivalent privacy and Wi-Fi protected access [99]. Specific virtual private network protocols, Secure Sockets Layer and related protocols (especially in the setting of hypertext transfer protocols), native apps, virtual desktops, and nonmedical commercial off-the-shelf apps merit consideration for data access and transfer [100]. Specific standards for hardware and software platform security, including prevention of hardware tampering, protection from malicious software, and application authentication methods, are vital to develop secure access for mobile imaging [99, 100].

Conclusions

This paper highlights existing and potential mobile applications used in imaging workflow to enhance patient care. For radiologists, the University of Washington has put together a list of 12 applications for everyday use [101]. The ultimate test is, however, end-user which means every and any medical personnel who works with the technology and every patient who uses it. The latter in turn provide feedback for improvement and this cycle facilitates constant evolution of applied technology in the field of radiology and medicine, in general.

The indispensability of the Internet and various mobile applications is facilitated by the government's push to incorporate information technology in healthcare [102]. Without such tools, it would be impossible to build the future of healthcare which is based on precision medicine intricately linked with radiomics and genomics, with radiology forming an important pillar [103]. Continued development on this front is hence warranted and needs to be budgeted for development of any radiology infrastructure.

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