Radiology Display Technology: Progress Over Time and the Role of Standards Today

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Abstract

Not long ago, X-ray information was recorded on film. Consequently, after development and fixation, post-processing of the image as we use today was simply only possible through another X-ray exposure with additional radiation and uncertain results. The introduction of the digital image information chain from the X-ray detector to the monitor has fundamentally changed this.

The digital transformation of radiology has been continuously expanded and improved through the application of new and increasingly powerful technical components. The omnipresence of radiological image information extends from the place of creation via PACS (Picture Archiving and Communication System) not only within the radiology department but also throughout the entire hospital and its departments, such as emergency room, operating room, wards, and outpatient clinics of the referring specialties.

Further dissemination of digital image information occurs via CD, DVD, USB sticks, and via the internet through patient and referrer portals. The end display devices of the image recipients/users can be projectors, beamers, computer screens, tablets, televisions, smartphones, or other electronic devices with suitable displays. In fact, visualizations of X-ray images on not-too-large displays like smart-phone displays or like displays of car radios are conceivable, for example, if a WhatsApp image message arrives via mobile phone to a radiologist driving a car.

Following the desires of the regulatory authorities, all these displays would have to be continuously checked for their display quality because it cannot be ruled out that an X-ray image might be displayed. Theoretically, this is conceivable. However, it is simply not feasible in our overregulated reality by now.

Fact-based arguments are discussed regarding this issue, covering various aspects of the diagnostic significance and the technical physical specifications of radiological images. Thus, we provide lawmakers and authorities with evidence-based facts to ensure that future legislative measures appropriately regulate radiologic display quality. Or even better: No need for regulations at all !?

Keywords: *digital image information chain, PACS (Picture Archiving and Communication System), electronic devices with suitable displays, projectors, beamers, computer screens, tablets, televisions, smartphones, diagnostic significance, digital revolution from 1987 to 2025.*

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Introduction

In 1987 Seeley et al. foresaw a bright and evolving future for all imaging techniques, especially radiology including new display technologies and computing power capabilities. However significant research and development are still required to achieve new display capabilities. Given the rapid advancements in computer technology and the fact that radiology is a field that thrives on cutting-edge innovation, it is highly likely that these and other, yet unimaginable, capabilities will eventually become a reality (42). Fig.1 shows a flow diagramm from 1987 in which Seeley et al. imagine that in the far future it may be possible to also add an expert system to the review console to aid the radiologist further in his diagnosis. Here is an improved version of your text with enhanced clarity, flow, and precision: "*The expert system will leverage automated feature extraction techniques along with data from the Hospital Information System (HIS) and Radiology Information System (RIS) to generate a probable diagnosis. This diagnosis can be accessed by the radiologist at any time and from any location.*"(42)

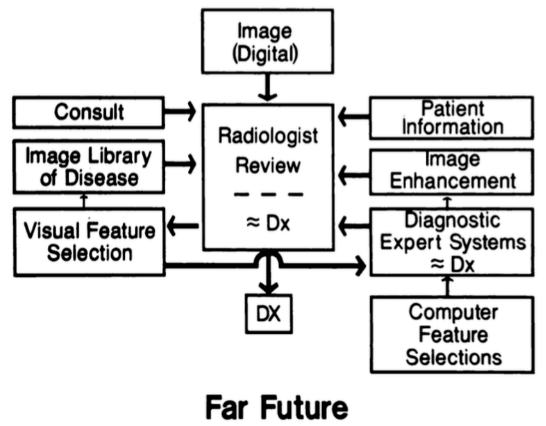

Fig. 1: In the far future it may be possible to also add an expert system to the review console to aid the radiologist further in his diagnosis. The expert system will use automatic feature extraction techniques and the HIS and RIS information to arrive at a probable diagnosis, which can then be accessed by the radiologist when desired (42). Starting point 1987.

As of 2025, nearly everything proposed by Seeley et al. in 1987 has become reality. Therefore, let us now turn our attention to the various display technologies and their evolution over the past decades.

Display Technologies

CRT - Cathode Ray Tube

A cathode ray tube (CRT) is a vacuum tube that was once the cornerstone of display technology in televisions, oscilloscopes, and early computer monitors. Its operation is based on the controlled manipulation of an electron beam (36, 35).
At the heart of a CRT is an electron gun, located at the narrow end of the tube, which emits a focused stream of electrons. These electrons are accelerated through a vacuum and steered using electromagnetic deflection coils (in most CRTs) or electrostatic plates (in oscilloscopes). The beam is directed toward a phosphorescent screen at the wide end of the tube. When the electron beam strikes the screen, it excites the phosphor coating, causing it to emit visible light (41).

Technical specifications of CRTs include the screen size, typically measured diagonally, the resolution, which depends on the fineness of the phosphor dots or stripes, and the refresh rate, commonly between 60 and 100 Hz. Color CRTs use three electron guns (one for each primary color: red, green, and blue) and a shadow mask or aperture grille to ensure precise alignment of beams with corresponding phosphor elements.
Other key parameters include deflection angle (e.g., 90° or 110°), aspect ratio (usually 4:3 or 16:9), and dot pitch, which determines the sharpness of the image. CRTs require high voltage, often 20,000 to 30,000 volts, to accelerate the electron beams.

Despite being bulky and power-hungry, CRTs offered excellent color rendering and fast response times, which made them superior for video applications until they were largely replaced by flat-panel technologies.

Flat-Panel Display Technologies

Flat-panel display technologies have fundamentally transformed how we consume information and interact with digital devices. Unlike their bulky cathode ray tube (CRT) predecessors, flat-panel displays are lightweight, energy-efficient, and capable of high-resolution output in compact form factors. They have become the visual core of televisions, smartphones, tablets, laptops, signage, and medical imaging systems.

Over the past several decades, a wide variety of flat-panel display technologies have emerged, each offering specific benefits tailored to particular applications. These advances reflect the interplay between physics, materials science, and electrical engineering. This overview traces the historical development of these technologies—

from early prototypes to today's cutting-edge innovations—while exploring their underlying principles, specifications, and market impact.

Early Flat-Panel Displays

A) Electroluminescent Displays (ELD)

Electroluminescent displays (ELDs) are among the earliest flat-panel technologies. First demonstrated in the 1930s and later refined in the 1960s and 1970s, ELDs use phosphor materials that emit light in response to an electric field.

Working Principle:

A thin film of phosphor is sandwiched between two layers of electrodes. When an alternating current is applied, electrons excite the phosphor atoms, which then release energy as visible light.

Technical Specifications:

Resolution: Typically low (e.g., 128×64 pixels)
Brightness: ~100–300 cd/m²
Color: Usually monochrome (amber, green, or blue)
Refresh rate: ~60 Hz
Power consumption: Moderate
Lifespan: ~10,000–30,000 hours

Use Cases:
-Industrial instruments
-Military displays
-Early aviation panels

ELDs were valued for their ruggedness and wide operating temperature range but lacked the resolution and scalability needed for consumer electronics.

B) Liquid Crystal Displays (LCD)

Liquid crystal displays (LCDs) revolutionized the flat-panel market starting in the 1980s. LCDs manipulate light using electrically controlled liquid crystals and a backlight source.

1. Twisted Nematic (TN) Panels

TN panels were the first commercially viable LCD type and remain in use today due to their low cost and fast response times.

Working Principle:

Liquid crystals twist the polarization of light. When voltage is applied, the twist is reduced, altering light transmission through crossed polarizers.

Technical Specs:
Resolution: Up to 3840×2160 (4K)
Refresh rate: 60–240 Hz
Response time: 1–5 ms
Contrast ratio: ~600–1000:1
Viewing angles: Narrow (160° horizontal)
Bit depth: Typically 6-bit + FRC

2. In-Plane Switching (IPS) Panels

Developed in the mid-1990s, IPS panels were designed to address TN's poor color reproduction and viewing angles.

Improvements:
Molecules remain parallel to the screen, rotating in-plane.
Wider viewing angles (178°)
Better color accuracy
Specs:
Response time: 4–8 ms
Contrast ratio: 1000–1500:1
Bit depth: True 8-bit or 10-bit
Color Gamut: sRGB, AdobeRGB, DCI-P3
Widely used in professional monitors, smartphones, and tablets.

3. Vertical Alignment (VA) Panels

VA panels offer a middle ground between TN and IPS, with deeper contrast and decent viewing angles.

Technical Highlights:
Black levels: Excellent
Contrast ratio: 2000–5000:1 (some advanced VA panels > 8000:1)
Color gamut: Wide, often DCI-P3
Response time: 4–6 ms (can be slower)
Ideal for TVs and home entertainment

C) Plasma Display Panels (PDP)

Plasma displays gained traction in the late 1990s and early 2000s, particularly for large-screen TVs.

Working Principle:

Each pixel contains small cells filled with noble gases. When excited by voltage, these gases ionize into plasma, emitting UV light that excites phosphors to produce red, green, and blue light.

Technical Parameters:
Resolution: Up to 1080p (some 4K prototypes)
Contrast: ~10000:1
Brightness: ~500–1500 cd/m²
Color depth: 8-bit or 10-bit
Burn-in risk: High
Lifespan: ~30,000–60,000 hours
Advantages:
Deep blacks and excellent motion handling
Superior color at the time

Plasma fell out of favor due to its bulk, power consumption, and eventual improvements in LCD and OLED tech.

D) Organic Light Emitting Diode (OLED)

OLEDs mark a major leap in display quality and design flexibility. First proposed in the 1980s and

commercialized in the 2000s, OLED panels emit light per pixel, requiring no backlight.
Working Principle:
Organic compounds emit light when subjected to electric current. Layers include emissive, conductive, and substrate layers.
Types:
PMOLED: Passive matrix; limited resolution
AMOLED: Active matrix; high resolution and widely used

Technical Specs:
Resolution: 4K and above
Contrast ratio: ∞ (true blacks)
Brightness: 600–1500 cd/m² (HDR OLEDs can exceed 1000 cd/m²)
Response time: <1 ms
Color gamut: Wide (DCI-P3, Rec. 2020)
Lifespan: 20,000–100,000 hours (blue OLED remains limiting factor)
Applications:
- Smartphones (e.g., Samsung Galaxy, iPhone)
- TVs
- Wearables
- High-end monitors
Advantages:
-Perfect blacks
-Flexible and curved displays
-Thinner and lighter

E) Quantum Dot Displays
Quantum dots (QDs) are nanoscale semiconductor particles that emit light when excited. They enhance color and brightness.

1. Quantum Dot Enhancement Film (QDEF)
This approach combines quantum dots with traditional LCDs.

Benefits:
Improved color gamut (up to Rec. 2020 coverage)
Increased brightness. More energy-efficient than standard LCDs.

2. Quantum Dot OLED (QD-OLED)
A hybrid developed by Samsung and others, QD-OLED uses blue OLED emitters with red and green quantum dots.

Specs:
True RGB pixels
No color filters
HDR peak brightness: >1000 cd/m²
Excellent color volume
More uniform lifespan compared to traditional OLED

QD-OLED began commercial deployment around 2022 and continues to evolve.

F) MicroLED Technology
Looking beyond 2025, MicroLEDs are increasingly seen as the leading candidate for next-generation premium displays.

Development:
Originating from research in the early 2000s, MicroLEDs have recently begun appearing in commercial products (e.g., Samsung "The Wall").

Working Principle:
Each pixel is a self-emissive micro-scale LED (inorganic gallium nitride).

Advantages:
High brightness: >2000 cd/m²
Infinite contrast
No burn-in
Long lifespan (>100,000 hours)
Response time: <0.1 ms
Color Gamut: Very wide (Rec. 2020+)

Challenges:
- Complex manufacturing (millions of microLEDs must be precisely placed)
- High cost
Applications are currently limited to ultra-premium or commercial displays.

G) Emerging and Experimental Technologies
1. Mini-LED
Mini-LED is an enhancement of LCD backlighting. It uses thousands of small LEDs to enable local dimming zones.
Specs:
Contrast ratio: Up to 100,000:1 (effective)
Brightness: 1000–2000+ cd/m²
Backlight zones: Hundreds to thousands
Better HDR support
Mini-LED serves as a bridge between LCD and MicroLED and is found in Apple's recent iPads and MacBook Pros.

2. Electrophoretic Displays (E-Ink)
Used primarily in e-readers and signage.

Working Principle:
Microcapsules contain black and white particles that move under electric fields.

Specs:
Resolution: ~300 PPI
Refresh rate: Very low (0.5–1 Hz)
Power: Near-zero when static
Monochrome (some color variants exist)

Technology	Contrast	Brightness (cd/m²)	Response Time	Color Gamut	Power Use	Flexibility	Burn-in Risk
TN LCD	600–1000:1	200–350	1–5 ms	Narrow	Low	No	No
IPS LCD	1000–1500:1	300–500	4–8 ms	Wide (sRGB, DCI-P3)	Moderate	No	No
VA LCD	2000–8000:1	300–600	4–6 ms	Wide	Moderate	No	No
Plasma	10000:1	500–1500	~2 ms	Wide	High	No	Yes
OLED	Infinite	600–1500	<1 ms	Very Wide	Low (dynamic)	Yes	Yes
QD-LCD	1000–1500:1	500–1000	4–8 ms	Very Wide	Moderate	No	No
QD-OLED	Infinite	>1000	<1 ms	Very Wide	Low	Yes	Lower risk
MicroLED	Infinite	>2000	<0.1 ms	Very Wide	Low	Potential	No
Mini-LED LCD	100,000:1*	>1000	1–5 ms	Wide	Moderate	No	No
E-Ink	N/A	Ambient light only	Very slow	Monochrome	Ultra-low	Flexible	No

Comparative Overview - Tabulated Technical Comparison

Table 1: Comparative Overview - Tabulated Technical Comparison

Ideal for reading and static content but unsuitable for video.

Table 1 provides a comparative overview of current flat-panel display technologies in a structured technical format.

Table 2 provides a comparative overview of the best-fit applications for current flat-panel display technologies, highlighting which technical approaches are most suitable for various consumer and professional product types available on the market today.

Best-Fit Applications	
Smartphones	OLED, AMOLED, QD-OLED
TVs	OLED, QD-OLED, Mini-LED
Monitors	IPS LCD, OLED, Mini-LED
Wearables	OLED, MicroLED (future)
E-Readers	E-Ink
Public Signage	MicroLED, LCD, ELD

Table 2: Best-Fit Applications

Summary of Flat-Panel Technologies

The journey of flat-panel display technology spans nearly a century—from early phosphor-based electroluminescent panels to self-emissive MicroLEDs and hybrid quantum dot systems. Each new technology has tackled previous limitations in brightness, resolution, color fidelity, and form factor.

LCDs remain dominant in cost-sensitive markets, while OLED and QD-OLED are setting benchmarks for visual quality. MicroLED holds enormous potential as it combines the advantages of OLED and inorganic longevity, though it remains prohibitively expensive for most consumers.

Looking ahead, advances in materials (such as perovskites and nanomaterials), flexible substrates, and AI-driven image optimization will likely define the next generation of displays. The goal is not just better visuals, but smarter, more immersive, and energy-efficient display systems that continue to reshape human interaction with the digital world.

Comparison of Color LCD and Medical-grade Monochrome LCD - Displays in Diagnostic Radiology

Digital radiology offers numerous advantages over traditional film-based methods. (38) One key benefit is the separation of functions that were once handled solely by the film. These functions are now divided into four distinct steps: data acquisition, image processing, data storage, and

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image display. Each of these stages can—and should—be individually optimized. In the final step, image display, the digital image conveys information to the observer, typically through variations in light and color on a screen. In summary, Geijer et al. found no significant difference in image quality between a medical-grade monochrome LCD display and a color LCD display with equivalent spatial resolution. This held true for both contrast-detail phantom testing and visual grading analysis, provided that the grayscale settings were fully optimized (38).

Widespread Use Cases of Display Technologies

Podcasting

Podcasting is an emerging internet-based broadcasting medium with distinctive features that offer promising applications in radiologic education. Podcasting represents a low-cost, efficient method for delivering audio-based educational content ("audiocasts") online. Its accessibility and ease of distribution make it a compelling tool for enhancing radiologic learning and outreach. When radiological images are presented in podcasts, the display quality of the viewing device is typically not prioritized, as these formats are not intended for diagnostic interpretation (39).

Who cares about display quality?

Acquiring and maintaining competency in radiology is a lifelong task that requires continuous learning. The authors want radiological images to be shared online for educational purposes, but no one mentions the quality of the monitors (37) or displays that learners have to work with. The use of two educator-centric learning management systems (LMSs)—Moodle and Manila—for radiology e-learning was formatively evaluated, and the (37) implications for future use of LMSs in radiology education were explored. NeuroRAD, a neuroradiology digital library and learning community, was implemented using Moodle, one of the most widely adopted open-source LMSs. In contrast, Pediatric-Education.org, a pediatric digital library and learning community, was built using Manila, a commercial educator-centric LMS (37). Quantitative and qualitative assessments of both LMSs were conducted using web server log file analysis and user-submitted feedback forms. In 2005, NeuroRAD attracted 9,959 visitors who viewed a total of 98,495 pages, while Pediatric-Education.org was accessed by 91,000 visitors who viewed 186,000 pages (37). Users represented a broad range of medical learners who engaged with the platforms to answer clinical questions, prepare for lectures, conferences, and informal teaching sessions, stay up to date, and study for examinations. Early findings suggest that radiology learning communities can be effectively and affordably developed using educator-centric LMSs, even by radiologists with limited technical expertise. These online communities have the potential to play a significant role in supporting radiology education globally, throughout a radiologist's professional life (37). Has the quality of monitors used by medical learners ever been given serious attention?

E-learning content should be simple to deploy, deliver, and access. It can be distributed via the Internet, institutional intranets, or desktop solutions, and accessed through various browsers on desktop computers, PACS workstations, mobile phones, and handheld devices. Additionally, e-learning can help reduce or eliminate language and accessibility barriers.
Many medical centers already employ SCORM-compliant Learning Content Management Systems (LCMSs) to fulfill educational requirements set by The Joint Commission (TJC) and the Occupational Safety and Health Administration (OSHA) for hospital personnel. SCORM, a modern standard for creating and delivering e-learning content, allows learning materials to be widely distributed, reused, or modified to suit different audiences. Utilizing SCORM standards has the potential to significantly improve e-learning effectiveness in radiology. (32)

American Board of Radiology criteria

Evaluation of Commercial Off-the-Shelf Displays for Use in the American Board of Radiology Main tenance of Certification (MOC) Examination.
The study from Krupinski et al. (34) prospectively assessed the diagnostic adequacy of high-, mid-, and low-resolution commercial off-the-shelf (COTS) displays commonly found in commercial testing centers. The primary objective was to determine whether these displays could reliably present key diagnostic features necessary for decision-making in the American Board of Radiology (ABR) MOC examinations, which employ a multiple-choice format (34).

The ABR's Psychometrics Division approved two HIPAA-compliant human observer studies. Each used radiological images from nine subspecialties. Observers viewed each image twice—once on each of two displays—and rated the visibility of critical diagnostic features.

Study 1 compared 1280×1024 and 1024×768 displays across 7977 paired observations. Iden-

tical ratings were recorded in 72% of cases. The 1280×1024 display received significantly higher visibility ratings in 19% of cases (P < .0001), whereas the 1024×768 display was rated superior in only 9%. All subspecialties except nuclear medicine demonstrated significantly improved visibility on the higher-resolution display (34).
Study 2 compared 1600×1200 and 1280×1024 displays across 1090 data pairs. Ratings were identical in 63% of cases. The 1600×1200 display was rated higher in 22% (P < .0001), while the 1280×1024 was rated higher in 15%. Statistically significant advantages for the higher-resolution display were observed primarily for cardiopulmonary and musculoskeletal images (34).

Patients?

Patients utilize healthcare technologies for various reasons. Recently, the Centers for Medicare and Medicaid Services released the Meaningful Use rule, providing initial guidance for patient-facing technologies. However, a deeper understanding of patient needs and the effective use of these technologies remains necessary. There is a framework to categorize patient-facing technologies based on their meaningful use and explores how these technologies can enhance healthcare quality, safety, and population health. Additionally, barriers to achieving meaningful use of Health Information Technology (HIT) and potential unintended consequences associated with patient-facing technologies are present. The success of healthcare reform depends on improving health outcomes and reducing costs, goals achievable only by actively engaging patients in their own care. Patient-facing technologies are expected to play a crucial role in helping patients become better informed and more engaged, potentially increasing overall efficiency (33).

Security?

The primary challenge in healthcare information security lies not in technology but in the absence of cohesive security policies. Security policies should guide technology implementation, not the other way around. These policies clearly define what needs protection, the extent of protection required, and the individuals authorized to access protected resources (31). Clinicians using mobile apps in radiology must be aware of essential security protocols designed to prevent unauthorized access. These include robust passcode policies, safeguards against repeated failed login attempts, network-managed passcode enforcement, and device-level protection measures to secure sensitive clinical data (24, 14).

Figure 2: Head-CT scan on smartphone

The interpretation of head CT scans for telestroke network patients by vascular neurologists using ResolutionMD™ on smartphones showed excellent agreement with interpretations made by spoke radiologists using a Picture Archiving and Communication System (PACS), as well as those by independent telestroke adjudicators using desktop viewers. In a telestroke network environment, VNs' noncontrast CT identification of radiological contraindications to thrombolysis of patients with acute stroke with ResMD™ on a Smartphone was in excellent agreement with those of spoke hospital radiologists and the independent telestroke adjudicators (30).

Apps?

Many medical applications for smartphones have been developed and widely used by health professionals and patients. The use of smartphones is getting more attention in healthcare day by day. Medical applications make smartphones useful tools in the practice of evidence-based medicine at the point of care, in addition to their use in mobile clinical communication. Also, smartphones can play a very important role in patient education, disease self-management, and remote monitoring of patients. Client applications for Hospital Information Systems (HISs), such as electronic health records (EHR), electronic medical records (EMR), and picture archiving and communication systems (PACS), provide the flexibility of accessing patient information securely from anywhere at any time. A total of five articles discussed the use of smartphones to access patients' clinical information. HIS client applications for smartphones provide some of the functionality of their PC counterparts. E.g. OsiriX

Mobile™ is the client application for OsiriX PACS™, which processes and displays images using the DICOM standard for digital image storage (29). 2017 an App Review of Management Guide for Incidental Findings on CT and MRI found it to be easy to use and named it an attractive app providing a simple clickable algorithm for incidental CT and MRI findings based on ACR white papers (5). The 2015 review of the Radiology Physics 300 app concluded that it is an easy-to-use tool offering a quick overview of radiology physics, featuring well-crafted multiple-choice questions accompanied by clear and informative answer explanations. (12)

The convenience and interactivity of the online world have significantly influenced consumer behavior, transforming the ways we purchase products and plan vacations. It is inevitable that consumers will soon demand healthcare services with the same ease of use they experience when booking flights or managing bank accounts. The healthcare industry itself relies on periodic and mandatory data analysis for outcomes assessment, clinical benchmarking, quality improvement, guideline development, and decision-making. Both the federal government and healthcare organizations are collaborating to develop more robust and cost-effective healthcare informatics solutions. The Meaningful Use (MU) initiative aims to establish new standards for healthcare informatics across the United States (28).

TABLE 3: Menu Set at a Glance: A Summary of the Features

Menu Set Measures	Potential Ease of Adoption by Radiologists Using a RIS with Modular EHR Certification
Medication reconciliation	Probably excluded
Summary of care record for each transition of care or referral	Probably excluded
Submission of electronic data to immunization registries	Probably excluded
Implement drug formulary checks	Probably excluded
Incorporate clinical lab test results into the EHR as structured data	Probably excluded
Capability to submit electronic syndromic surveillance data and actual submission according to applicable law and practice	Probably excluded
Use certified EHR technology to identify patient-specific education resources and provide those resources to patients if possible	May conflict with clinicians
Provide patients with timely electronic access to their health information (including lab results, problem list, medication lists, and allergies) within 4 business days of the information being available to the eligible physician	May need a patient portal. Outside the purview of radiologists
Send reminders to patients for preventive and/or follow-up care	Very difficult to apply to 20% of all patients
Generate lists of patients by specific conditions to use for quality improvements, reduction of disparities, research, or outreach	Available as third-party options outside of PACS.
HER, Electronic Health Record; PACS, Picture Archiving and Communication System; RIS, Radiology Information Systems	

(28)

The rapid adoption of new technology has significantly transformed our culture, commerce, and communication, and holds the potential to revolutionize medical education and practice. This study (27) examined how medical educators and learners currently utilize mobile computing devices, such as iPhones™, in medical education and clinical practice, and explored their anticipated future applications (27).

Key messages are: Mobile computing devices are rapidly becoming commonplace in clinical settings. This emerging technology has the potential to enhance medical education and patient care but also brings possible challenges. Policy-makers should actively engage with users to understand their needs, ensuring the technology's benefits are maximized while minimizing unintended consequences. Mobile computing devices have been rapidly adopted by medical learners and teachers at researcher's school, and it seems likely that their presence will soon be ubiquitous. This new technology offers the potential to enhance learning and patient care, but also has potential problems associated with its use, and may redeme how we manage information in medicine (27).

Figure 3: Sonography of liver on smartphone

Smartphone applications (apps) for radiologists are increasingly popular (26). These apps assist radiologists not only by providing quick reference information but also by enhancing daily workflow, particularly through image viewing applications known as Digital Imaging and Communications in Medicine (DICOM) viewers. This development signals a shift toward an increasingly mobile medical environment, presenting both exciting opportunities and significant concerns for radiologists. In conclusion, radiology currently benefits from a broad selection of useful applications that can be employed by both experienced radiologists and medical professionals in training. Given the growing number of app developers, there remains considerable potential for further innovation, and there is no reason why radiologists themselves should not assume a leading role in

the development of such tools. Limitations in image interpretation on smartphones represent a drawback of DICOM viewer applications. The ethical and legal implications associated with the expanding use of smartphone apps in clinical practice warrant further investigation (26).
Certain measures can be taken to ensure the secure transfer of information over public and home networks, especially in light of the growing use of mobile devices in radiology. As radiology continues to advance technologically, a solid understanding of key technical principles is essential for practicing radiologists. The use of mobile devices—such as laptops, tablets, and smartphones—for interpreting radiologic studies has become increasingly common, despite the varying quality of display systems on these devices (24).
Radiology training programs nationwide are increasingly equipping residents with iPads and other mobile devices. Yet, many lack a clear strategy (40) for integrating these tools into a cohesive educational framework. One effective application is video recording of lectures, which offers several advantages. It provides access to educa-tional content for residents unable to attend in person due to vacation, post-call fatigue, or procedural duties. Moreover, recorded lectures can be reviewed anytime, at any pace, supporting flexible, self-directed learning. Mobile devices naturally complement this mode of study, encou-raging independent learning in a more accessible, user-friendly format. Still, integrating new technologies into the radiology education workflow is not without its challenges—there's a steep learning curve and numerous potential barriers to adoption. Nonetheless, mobile technology is not a passing trend; it's a permanent fixture. What's needed now is a clear, purposeful vision for how these tools can enrich the educational journey of radiology residents. By leveraging their capabilities to modernize teaching and close the gap between clinical practice and digital learning, we can help ensure a bright and evolving future for radiology education (25).

Portals?

Current evidence remains limited regarding the impact of patient portals on health outcomes, healthcare costs, or service utilization. While patients generally view these tools positively, broader adoption may hinge on addressing barriers related to race, ethnicity, and health literacy. As a relatively new technology, the tangible benefits of patient portals are still not well defined. A more comprehensive understanding will require studies that account for contextual factors, implementation strategies, and associated costs (23). Handheld computers and mobile devices offer healthcare professionals immediate access to a wide range of valuable clinical information. Their compact size and enhanced processing capabilities have driven rapid integration into clinical settings. As their use becomes more widespread, it is essential to assess their true effectiveness in everyday practice. Mobile health (mHealth) technologies and handheld devices support healthcare delivery across all core aspects of patient care. They enable real-time access to evidence-based decision support tools and patient management systems—such as PACS (Picture Archiving and Communication System)—thereby enhancing diagnostic accuracy and clinical decision-making (22). The Medical Devices Directive (MDD) aims to ensure the safety and performance of medical devices across the European Union.
Although the directive provides a unified framework, each member state maintains its own regulatory system, and no consensus currently exists on what constitutes a "medical device"—particularly in the context of medical software and applications. This lack of clarity creates uncertainty for app developers and healthcare providers alike. For example, in the UK, the Medicines and Healthcare Products Regulatory Agency (MHRA) classifies DICOM viewing applications as medical devices.

All medical devices marketed in the EU must bear the CE (Conformité Européenne) mark, indicating that the manufacturer affirms compliance with the relevant legislative requirements. These requirements depend on the risk classification of the device under the MDD. Most medical applications, including DICOM viewers, fall into the lowest risk category (Class I), allowing developers to self-certify compliance without independent assessment. Despite this, CE marking remains uncommon in app stores (21).
The ability to access high-resolution medical images remotely via smartphones carries potential benefits for timely diagnosis and treatment. However, there are significant limitations that must be acknowledged. First, there is a lack of robust evidence regarding the diagnostic accuracy of image interpretation on smartphones. Second, smartphones typically fail to meet the minimum technical standards required for primary diagnostic displays in Europe.
For instance, the Royal College of Radiologists (RCR) mandates a minimum screen resolution of 1,280 × 1,024 pixels and a screen size of at least 42 cm, with functionality for side-by-side comparison of serial studies. In contrast, the iPhone 5, for example, has a resolution of 1,136 × 640 pixels and a screen size of only 10.2 cm.

Additional concerns include the adverse impact of ambient lighting on image quality and the absence of the rigorous calibration and quality assurance protocols that standard reporting workstations undergo. To be used for primary diagnosis, smartphones would need to be integrated into similar quality control systems.

Therefore, despite FDA approval of certain mobile DICOM viewers, caution is warranted when considering their use for primary diagnostic purposes on smartphones. Due to inherent display limitations, smartphones are better suited for image review rather than diagnosis. While radiologists are typically aware of these constraints, other healthcare professionals may not fully recognize the associated risks and limitations (21).

Smartphones and tablets open up new possibilities for professionals in diagnostic imaging (20). With their intuitive interfaces and high-quality displays, these portable devices can be used not only for diagnostic image review, but also for reference, education, clinical consultations, and even patient communication.

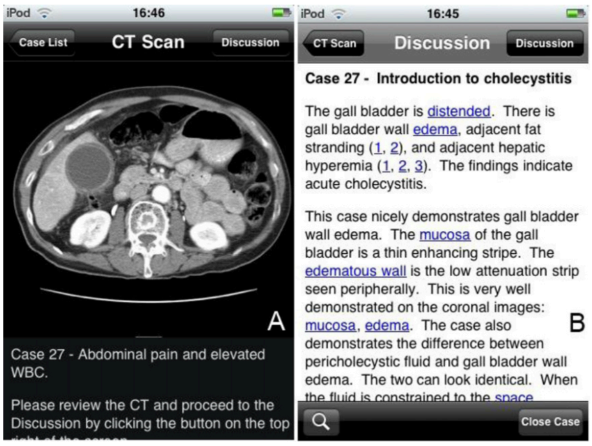

Figure 4: CT-scan on iPad with discussion (20)

Focused ultrasonography of the airway may be useful in the prediction of difficult intubation. Mobisante MobiUS™ system was able to acquire clinically useful images of the suprahyoid airway and muscular architecture in the mouth floor and allowed accurate measurements of linear distances for easier intubation access (19).

Internet?

When personal computers first emerged, they were designed primarily for individual use. But as inherently social beings, humans quickly sought ways to connect—and the internet made that possible. The rise of mobile IT devices accelerated this trend, enabling like-minded individuals to connect, collaborate, and form functional units within a shared digital space.

Today, it's becoming routine for colleagues to exchange materials via cloud platforms and work together on complex projects, regardless of physical location. The idea that "humans are social animals" reflects a deep-rooted drive for communication and collaboration. Looking ahead, this instinct will continue to shape our relationship with technology. IT devices, cloud infrastructure, and collaborative software will remain central tools for connection, coordination, and collective progress. We were never meant to work in isolation (18). Within parts of the medical community, the iPad is seen as a transformative tool in healthcare deli-very—particularly in the field of medical imaging, where its versatility supports a wide range of applications (17).

Dams et al. demonstrated that, despite substantial price differences, the LCD monitors evaluated showed no significant variation in image quality. Therefore, when selecting an LCD display, factors beyond the initial cost—such as long-term maintenance expenses and system stability—should also play a key role in the buyer's decision-making process (16). Audience Response Systems (ARS) offer a valuable means of enhancing interactive learning among radiology residents. Yet, it is the underlying pedagogy—not the technology itself—that ultimately determines educational effectiveness. Simply put, it's time we bring our teaching strategies up to the same standard as our ARS tools (15). While mobile devices offer clear educational benefits in radiology, several limitations must be acknowledged.
Currently, there are no regulatory standards ensuring the accuracy or reliability of radiology apps. As barriers to app development continue to fall, the quality of available apps remains highly inconsistent—a fact the authors have experienced firsthand. Trainees may encounter a range of issues, including suboptimal image quality, missing radiographic examples, outdated guidelines, inaccurate content, or lack of proper referencing. These challenges are not unique to radiology; they reflect broader concerns across medical apps. Efforts are underway to establish frameworks that can help assess and improve app quality in the absence of robust regulatory oversight. Advancements in hardware and increasing screen resolution are expected to significantly enhance mobile image quality in the future (13).

Digital Divide?

The digital divide is well-documented and continues to raise concerns that certain patient

groups may disproportionately benefit from access to patient portals. There are findings that indicate regular internet use and ownership of a personal computer partially explain disparities in portal use for messaging healthcare providers—particularly across age, race, and income groups. However, differences related to education and sex remained statistically significant even after accounting for internet access and care preferences.
As patient portals become more widespread, it is critical to identify which populations face limited access and to understand the barriers they encounter. Addressing these disparities will require expanding internet access across diverse sociodemographic groups, designing intuitive and inclusive portal interfaces, and ensuring seamless access across multiple platforms—including mobile devices. These measures could play a key role in reducing inequities in the use of secure messaging and digital health communication (11). A patient-directed, interoperable, internet-based image-sharing system is both feasible and offers superior accessibility compared to traditional CD-based methods, while maintaining comparable levels of patient satisfaction regarding privacy (10).

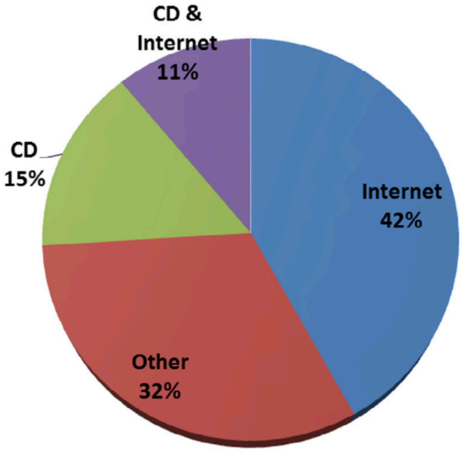

Figure 5: Modality used by patients to share their medical images with their physicians (10)

According to findings from Greco et al. patients are actively engaging with the patient portal to communicate with their care providers about radiology studies. Analysis of the extracted data reveals that patients place high value on timely access to and clear understanding of radiologic information. The evidence strongly suggests that those who use the portal to reach out to their physicians regard diagnostic imaging and test results as important to their health and well-being—and they seek to minimize delays in receiving this information. These insights provide indirect yet compelling evidence that patients see radiology as central to their care. By examining these communication patterns and priorities, we can better identify opportunities to enhance patient-centered radiology services (9).

Since the late 1990s, mobile devices, wireless networks, and software have advanced significantly, reaching a level of speed, processing power, and sophistication that now enables real-time interpretation of radiologic studies. Given the time-critical nature of emergency radiology (ER), mobile interpretation aligns well with the need for rapid, on-the-go diagnostic input—allowing radiologists to read studies anytime, anywhere.

While these devices are well-suited for use by radiologists outside the hospital and by clinicians or surgeons at the bedside or in the operating room, they still come with limitations. Regulatory approval for primary diagnostic use within hospital settings remains limited. In the context of emergency radiology, we propose that one of the most valuable uses of mobile devices lies in enhancing communication—specifically, enabling radiologists to consult directly with patients about their imaging results and to engage with the clinical team during rounds and handovers. This approach not only deepens our understanding of the patient's presentation but also supports education for both patients and providers, while increasing the visibility and perceived value of the radiologist as an integral member of the clinical care team (8). Today, we are confronted with an explosion of data, and the challenge lies in how to effectively integrate, analyze, and interpret it. A key priority is the ability to distinguish meaningful information from "noise" in order to reduce the risk of mis-interpretation and diagnostic error (7).

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While mobile device screens are not suitable for the primary interpretation of projectional radiographs or mammography, their resolution, luminance, and pixel size are generally sufficient for technically adequate display of computed tomography (CT) examinations. Several studies have demonstrated that CT interpretation on high-quality tablet screens is feasible. However, it is not recommended for primary diagnosis due to several potential limitations.
One key concern is screen cleanliness: the touchscreen interface, manipulated by fingertip contact, can easily accumulate smudges that obscure fine image details. Moreover, while stationary radiology workstations allow for controlled ambient lighting, such control is not possible with mobile devices. This is particularly relevant as tablets often have glossy screens, which are

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more prone to distracting reflections than standard workstation monitors. As a result, tablet-based CT interpretation may only be appropriate under optimal viewing conditions—and even then, with caution (6). To successfully integrate new imaging technologies into routine clinical practice, radiology leaders must take an active role from the outset—starting with regulatory approval, continuing through early clinical validation, and extending to securing reimbursement and engaging key stakeholders to drive broad adoption (4).

Silosky et al. published performance characteristics and quality assurance considerations for displays used in interventional radiology and cardiac catheterization facilities. While display performance for image acquisition and primary diagnostic interpretation has been extensively studied, limited data exist on displays used in Interventional Radiology (IR) suites and Cardiac Catheterization (CC) laboratories. This study aimed to evaluate the performance of large-format displays in these environments and to explore the challenges of implementing display quality assurance (QA) protocols. Ten large-format displays from IR and CC suites were assessed. Visual inspection using test patterns was followed by quantitative analysis of key performance metrics, including luminance ratio, luminance response function, and luminance uniformity. Ambient lighting conditions were also measured. Luminance ratios ranged from 243.0 to 1182.1 (mean: 500.1 ± 289.2). Deviation from the DICOM Grayscale Standard Display Function ranged from 11.2% to 38.3% (mean: 26.2% ± 10.9%). Luminance uniformity showed a mean maximum deviation of 13.2% ± 3.5%, and an average deviation from the median luminance of 7.8% ± 1.0%. Ambient light levels varied widely (29.1 to 310.0 lux; mean: 107.6 ± 80.4 lux). While no mura or dead pixels were identified, physical damage such as scrapes, scratches, and smudging was common. Silosky et al. provide essential baseline data on the performance of large-format displays in IR and CC suites. These findings may serve as benchmarks for developing and implementing display QA programs tailored to interventional environments (3). Current and emerging mobile applications integrated into the imaging workflow serves to enhance patient care. At the practitioner level, the University of Washington (2) has curated a list of 12 mobile apps tailored for daily radiology use. Ultimately, though, the most important evaluators are the end users—both healthcare professionals who engage with the technology and the patients who interact with it. Patient feedback, in particular, plays a crucial role in refining these tools, fostering an ongoing cycle of improvement and innovation in applied medical technology. The growing indispensability of the Internet and mobile applications in healthcare has been further accelerated by government initiatives promoting the adoption of health information technology. These digital tools are foundational to the future of healthcare, which increasingly depends on precision medicine—anchored in radiomics, genomics, and advanced imaging. Radiology stands as a central pillar in this evolving ecosystem. Sustained development in this area is not only necessary but must be factored into the planning and budgeting of any future radiology infrastructure (2).

Regulatory authorities, long accustomed to evaluating the safety and efficacy of static, fixed-function medical devices, now face the complex challenge of overseeing the dynamic and mobile, ever-evolving nature of artificial intelligence (AI) on mobile devices in healthcare. In response, Australia's Therapeutic Goods Administration (TGA) has begun to articulate clearer regulatory expectations for AI-enabled medical devices. The TGA emphasizes that proactive engagement, staying informed about emerging regulatory frameworks, and seeking pre-submission consultations can be effective strategies for navigating this evolving regulatory landscape (1).

Conclusions

Radiological displays have historically required rigorous and continuous quality control (QC) to ensure accurate and reliable interpretation of diagnostic images. Traditionally, regulations mandated frequent QC procedures due to inherent limitations in early display technology, such as inconsistent luminance, inadequate resolution, and variability in grayscale representation. However, with recent technological advancements, contemporary display systems used in radiology —particularly for Computed Tomography (CT) and Magnetic Resonance Imaging (MRI)—have significantly surpassed previous generations in terms of reliability, image consistency, and diagnostic accuracy.

Modern high-quality radiological displays, including commercial off-the-shelf (COTS) monitors, inherently offer stable luminance levels, high resolutions, accurate grayscale rendition, and uniform brightness across the entire screen. The significant improvements in Liquid Crystal Display (LCD) and Organic Light Emitting Diode (OLED) technologies, along with built-in digital imaging

and communications in medicine (DICOM) calibration capabilities, ensure these displays consistently meet the stringent standards required for accurate diagnosis without frequent manual recalibration.

Studies assessing diagnostic efficacy demonstrate that current display systems reliably present CT and MRI images without significant loss of diagnostic information. Observational studies comparing diagnostic performance across varying resolution and luminance specifications have consistently found minimal to no clinically meaningful differences when using modern displays. Consequently, this renders frequent QC procedures redundant, leading to unnecessary resource utilization and associated costs without a measurable clinical benefit.

Moreover, display manufacturers have implemented robust internal mechanisms such as automatic luminance correction, built-in sensors for ambient light adjustments, and real-time quality monitoring tools. These automated processes continuously verify optimal display performance, effectively eliminating variability due to user or environmental factors. Such self-monitoring features further diminish the practical necessity for external, repetitive QC protocols.

Additionally, reducing overregulation in display QC protocols aligns well with modern healthcare trends emphasizing resource optimization and cost-efficiency. Continuous QC checks, previously justified by inferior technology, now constitute a regulatory burden, draining healthcare resources without commensurate improvements in diagnostic outcomes or patient safety.

While maintaining appropriate initial acceptance testing and occasional spot checks remains prudent, mandatory continuous quality controls for radiological displays—particularly regarding CT and MRI interpretation—should be reconsidered and scaled back. Modern display technologies inherently provide stable, high-quality diagnostic imaging, rendering the traditional paradigm of rigorous ongoing QC measures obsolete. Regulatory frameworks should evolve accordingly, reflecting current technological realities and promoting resource-efficient practices without compromising diagnostic accuracy or patient care.

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