Power System Technology
ISSN:1000-3673

Received: 06-02-2025 Revised: 15-03-2025 Accepted: 11-04-2025

Cardiac Imaging in the Digital Age: A Multidisciplinary Intersection of Radiology, Pharmacy, Informatics, and Echocardiography

Abdullah Omar Albedah[1], Abdullah Monahi Albogami[2], Sarah Talal Al-Anazi[3], Maryam Saleh Fallatah[4], Sultan Mubarek N Aldossary[5] Khaled Shayem Othman Alrashidi[6] and Nourah Alqanoor[7]

[1] Corresponding Author, Pharmacist, King Abdulaziz Medical City

[2,4] Pharmacist, King Abdulaziz Medical City

[3] Echocardiography, National Guard Hospital

[5] Specialized Radiology, Sulayil general hospital

[6] Specialist radiological technology, Buraidah Central Hospital, Al-Qassim Health Cluster

[7] Health Information Tech, King Abdulaziz Medical City

Abstract

During the past two decades, the advent of digital technologies has transformed the practice of cardiac imaging and redefined models of care. In this multidisciplinary overview, I present the global changes, challenges, and opportunities of cardiac imaging in the digital era. The scope of the discussion spans innovations in radiology, pharmacy, informatics, and echocardiography. The rapid integration of artificial intelligence and digital health—including telemedicine and electronic patient records—across the entire imaging ecosystem amplifies the urgency of this exploration. The modern cardiologist must grapple with these developments and their implications for patient care. A series of overarching questions captures the essence of these explorations: What are the key data sources, standards, metadata, analytics, and governance? What imaging modalities and digital integration concerns require attention? How can pharmacist expertise enhance the safe and effective use of contrast agents? What team compositions, workflows, and care pathways optimize collaboration, communication, and patient-centered outcomes? What opportunities and challenges do artificial intelligence and decision support systems present? What tools, technologies, and knowledge facilitate the transition to digital-to-digital workflows? What safety, privacy, and ethical considerations must inform the use of imaging-related data and artificial intelligence? What competencies underpin pre- and post-graduate training for a digitally informed workforce? What emerging trends, technologies, and research questions shape the horizon of cardiac imaging? As cardiologists reckon with these issues, an expansive set of scholarly works will survey the transformations, impacts, and futures of cardiac

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imaging in the digital age (Pepe et al., 2023) ; (Seetharam et al., 2020) ; (Westwood et al., 2023).

Keywords: Cardiac imaging, digital health, radiology, pharmacy integration, medical informatics, echocardiography, multidisciplinary collaboration, cardiovascular care, digital transformation.

1. Introduction

The digital era is defined by a radical transformation in the way images are generated, transmitted, stored, and analyzed. This transformation greatly affects the field of cardiac imaging. Radiology submitted to a comprehensive review has undergone considerable changes in cardiac imaging in the digital era. Cardiac Imaging has evolved to center on the evaluation of cardiac structure and function and the diagnosis of ischemic heart disease.

The ways images are generated, transmitted, stored, managed post-examination, analyzed, and reported, have dramatically changed. Many different imaging modalities for cardiac imaging are available in clinical practice. The emergence of highly sophisticated imaging equipment capable of obtaining and delivering sound and solid, high-quality images of cardiac anatomy and physiology and the steady decrease in the cost of computer processors and computer chips have made cardiac imaging even more established as a specialty.

The digital era has ushered in the mechanisms for standardizing and sharing not only the images, but also the associated clinical information, which has had a major impact in the clinical arena. Even the old memories of chemical film reminiscent of the dinosaur age, images are wholly digitized. Digital Imaging and Communication in Medicine (DICOM) provides a technical standard that promises the smooth interchange of images and associated metadata across different digital platforms. The Picture Archive and Communication System (PACS) have revolutionized not only the field of radiology, but also the field of cardiology (Westwood et al., 2023).

The advent of cloud-based systems and streaming technology is moving the whole concept of PACS and even the consideration of digital imaging of images into a totally different dimension. The radiologists are also classified into different categories depending on the MODE of the work performed such as full-time, part-time, teleradiologists, and remote-based. Tele-radiology has also advanced to the point that the possibility of being able to deliver the highly sophisticated understanding of cardiac imaging from one country to different continents is possible and is undergoing validation of such a state.

2. Radiology in the Digital Era: Transformations and Implications

Digital radiology plays a pivotal role in modern image generation, archiving, and sharing across healthcare institutions. Digital images are acquired from radiography, fluoroscopy,

Received: 06-02-2025 Revised: 15-03-2025 Accepted: 11-04-2025

computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound. These images are viewed on computers that employ electronic display technologies such as cathode ray tube analogue, liquid crystal display (LCD), or light emitting diode (LED). Images are stored in digital archives known as picture archiving and communication systems (PACS). The earliest PACS developed during the 1980s employed local area networking for connectivity. More recent systems implemented broader area networking, enabling digital imaging and communication of medical PACS to operate independently of proprietary hardware manufacturers, thereby meeting the need for digital transmission, storage, and technologist-assisted interpretation. The transition to cloud-based PACS offered additional benefits like rapid access to stored images for both routine and urgent cases, at-risk source code mitigation for obsolescence and ransomware attacks, and infectious disease mitigation by eliminating on-site equipment (Pepe et al., 2023). Image streaming capability is an emerging trend that allows outside images to be viewed by expert radiologists at remote sites for secondary interpretation. A surrogate approach—known as video conferencing or desktop screen sharing—mimics image streaming by viewing the PACS operator's screen on an external monitor (Nalin Shah, 2013). Concurrently, embedded video intercom permits real-time dialogue with technologists. Some systems are under evaluation for integration into standard workstation software.

The digital transformation has engendered major workflow and practice changes within radiology. In parallel with the introduction of more sophisticated imaging hardware (CT, MRI, angiography), image acquisition protocols have become increasingly complex. The number of parameters that can be modified now encompasses dozens to over a hundred, necessitating standardization to ensure high-quality imaging. Several nationally convened working groups have convened to produce consensus documents that specify, for selected studies (e.g., chest, abdomen), the precise settings that should be employed. These documents further propose default protocols, which can then be readily modified by technologists and subsequently re-saved or added to a library of user-defined defaults. Accordingly, modality-based standard protocol libraries are becoming common, with comprehensive multi-slice CT generic protocols established during early efforts. Archive database contents can be exchanged between different institutions using cross-enterprise document sharing and health level 7 (HL7) protocol; these same technologies support interchange among different PACS. Direct image exchange capability with several non-local facilities has further materialized through the adoption of the imaging transcoding service.

Radiology's evolving architecture has prompted significant attention to quality assurance, seeking to maintain examination accuracy and throughput at levels comparable to those enjoyed prior to the introduction of digital imaging. Quality control encompasses traditional equipment performance measurements, plus additional evaluations related to PACS, cloud, and streaming software, input and output display, viewing environments, and interpretive

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reporting. Radiology has long adopted standard measurements (e.g., modulation transfer function, contrast-to-noise ratio) to quantify, benchmark, and enhance image acquisition technology. Most commercial vendors now provide these tests within their systems. Enhanced sensitivity, augmented by preclinical, phantom, or retrospective clinical validation, determines incremental value contribution volumes for a variety of techniques. Meticulous acquisition and evaluation of observational data collected with PACS, cloud, and streaming is essential, as for a comprehensive list of controls.

Radiology's evolution has substantially transformed image accuracy and throughput at many centers, boosting clinical workflow. Daily case volumes monitored over years show striking growth in the multitude of studies recorded. Such increases stem from excessive interpretation demands, due to growing scanning capability coupled with scarcity of interpreting radiologists.

3. Pharmacological Considerations in Cardiac Imaging

Cardiac imaging supports the diagnosis, risk stratification, and management of cardiovascular disease and encompasses various modalities, including radiological techniques (R. Braga et al., 2019). Imaging protocols often require the administration of radiopharmaceuticals and contrast agents, highlighting the importance of pharmacological considerations (Nalin Shah, 2013). Radiopharmaceuticals are discussed in the imaging context but do not meet the terminology's strict definition (Westwood et al., 2023). Cardiac imaging procedures also employ non-radiological pharmacological therapies, which the immediate following sections also cover.

Cardiac imaging involves distinct contrast agents, doses, safety profiles, nephrotoxicity risk stratifications, and pharmacokinetics that impact imaging protocols. Regulatory and stewardship aspects further influence use and indicate the critical need for comprehensive medicines-related Knowledge for Capability Maps and a pre-established relationship among radiology, pharmacy, and cardiac imaging.

4. Informatics and Data Science in Cardiac Imaging

Clinical imaging generates data for routine use and secondary considerations. Data acquisition platforms generate non-image data alongside the images, such as timestamps, modal specifications, and acquired parameters to allow personnel to be cognizant of specific clinical factors. Modern modalities also have associated non-imaging data residing on systems that do not deal with imaging either from legacy environments or from the clinical environments. Such data provides additional context to the images, supporting reuse for pharmaceuticals, change management, and scenarios like remote surgical assessment.

Because imaging encompasses more than just generating the images, the image and the associated content constitutes a multimedia in this environment. While DICOM has long

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been the standard for image representation, it does not cover all variable types from a single use. Sensor and metadata models have emerged that consider the variation and adaptation, leading to open-source approaches. The constant generation of imaging data creates a significant burden for the storage, capability, and management of imaging data, along with an ongoing usage challenge. Therefore, images are part of the broader electronic health record.

Existing frameworks, such as DICOM and FHIR, provide a basis that institutions can adapt to improve usage and understandability across platforms and modalities. Regardless, the sheer quantity of the data remains prohibitive for analysis on any general workstation. Reproducibility is a significant challenge due to use conditions, metadata persistence, and efforts devoted to validation. Data-sharing frameworks are rapidly evolving to address some of these challenges. Centres are considering common acquisition setups to facilitate multi-centre evaluation, re-organisation to accommodate normal variations, and model, condition, or algorithm exchanges for multi-party collaboration (Zihad Bin Jahangir et al., 2023).

5. Echocardiography: Innovations and Digital Integration

Advances in transducer technology and digital integration enable new echocardiographic applications beyond traditional clinical service provision. Microvessels are invisible in routine echocardiography and advanced imaging is limited in routine practice due to dedicated ultrasound resources and expertise. These insights refine the pace of digital integration, enhance quality assurance through automated analysis of Doppler spectrum ratio across sites, and inform standardization needs for pre-analytical factors, raw files, and multi-dimensional video files even in global networks. Advanced transducer technology ameliorates logistical constraints and extends echocardiography's role in multiparametric imaging, structural monitoring, and functional monitoring. Digital integration facilitates advance monitoring outside conventional service hours, remote quality control, and large-scale applications with diverse multimodalities. A fully automated ultrasound supported by machine-learning algorithms identifies optional probes for standard view acquisition from low-dimensional raw data, accelerating routine-monitoring implementation.

Pioneering efforts on 3D and 4D echocardiography demonstrate corresponding developments in automation, assurance, and transmission. Automated 3D full-volume acquisition with automated rendering achieves moderate and consistent performance in leveling, foreshortening, and surface reconstruction. Fully automated 4D echocardiography conducted on fast temporal raw data preserves all original information and relentlessly accelerates monitoring. Continuous translational science and innovation yield alternating-pulse tissue Doppler mapping (Nalin Shah, 2013) for Doppler-quantity generation independent of B-mode images, multipoint Doppler acquisition, and sound-speed inversion for arbitrary wavefront-reconstruction from scattered point data. AP-TDM automates Tacoma Score estimation for long-axis-disease quantification across echo and MRI datasets. Multi-

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dimensional real-time transmit, 3D foreshortening-control, and vibration deactivation substantially improve Doppler-quantity acquisition on pneumatic and portable systems attached to shocking circuits.

6. Multidisciplinary Collaboration: Models of Care and Communication

Multidisciplinary teams represent an effective approach to integrate cardiac imaging and provide maximum benefit to patients. Models of care and communication, traversing across sectors of health and big Data, define radar cartography for structuring and organizing individual contributions within the collective system.

Efficient team compositions consider the scope and center of care activity, participant activities, and patient roles. Digital imagery and pharmacology shape specific radiology-echocardiography-share-flow health paths, where hyperbole and non-destructive laboratory work is addressed by imaging, and arrhythmia and obstetric matters are addressed separately as the response mandates drawing-in the card quantities to certain patterns of arrangement. Regulatory scrutiny can be relevant, even through inquiry does not explicitly proceed upon that configuration of team-building. Cardiologist participation fulfils the circumscription on unitary imaging; three domains matter concurrently, and inquiry is constrained to the Loch-side centre. Cardiac modelling links wider accessibility to data and preservation of diagnostic quality; projections change timeframes and allow wider attendance to spatial dynamics. Whenever sizeable action assembles within rail, central functions often establish template variants to guide configurements, and quite a number of regulatory agents become implicated. Inter-Cabré paths traverse medicine-technology dualities or radiology-pathology alternatives. Patterns of access through pharmacy-pharmacology direct informatics-protocol-sharing upflow; technology invariates indicate repetitive enactment or response. Presentation rivers circulate befores, and cross-system learnt patterns in feedback and simulation can be informative.

7. Artificial Intelligence and Decision Support in Cardiac Imaging

Artificial intelligence (AI) and machine learning (ML) permeate nearly all sectors of healthcare and substantially redefine diagnostic paradigms (Seetharam et al., 2020). In cardiac imaging, they enable analysis of multi-dimensional cardiac imaging datasets that exceed human interpretative capability and facilitate automation of tedious and repetitive tasks (Rudnicka et al., 2024). In the current state of continuous learning, enormous volumes of training data are needed, and feature extraction is performed manually by expert human interpreters. Although performance in these workflows can eventually exceed that of seasoned practitioners, interpretability and bias remain major issues (E. Yoon et al., 2021).

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8. Patient Safety, Privacy, and Ethical Considerations in a Digital Environment

The digital infrastructure supporting cardiac imaging relies on the capture, processing, storage, and distribution of massive quantities of data. Whether derived from images, patient records, laboratory tests, physiological signals, or genomic analyses, this concentration of information presents both opportunities and risks. On the one hand, sharing these data across sources enhances their diagnostic value and facilitates population-based studies. On the other, considerations of patient privacy and consent, the risk of exposure and misuse of sensitive data, and the ethical use of imaging information for artificial intelligence and machine learning models all raise important questions that require timely answers. Unless adequate solutions are found, the failure to appropriately address these concerns will stifle progress in imaging and inhibit public trust in its application.

The introduction of advanced imaging modalities and artificial intelligence for image processing has raised question around patient safety and the appropriateness of imaging studies performed. Although technology has simplified procedures, making them more accessible to patients and physicians alike, it is crucial to ensure that the necessity of imaging examinations is duly considered, in accordance with the principles of good radiation protection and the principles of the "as low as reasonably achievable" dose limit. Risk management guidelines help to define adequate procedures to minimize the likelihood of risk and its effects, and should be seen as complementing the accreditation of institutions and the implementation of safety and quality assurance procedures. The collection of large amounts of sensitive medical data opens up questions about patient consent for the inclusion of personal data and the use of algorithms in decision-making processes.

9. Education and Training for a Digital Cardiac Imaging Workforce

Cardiovascular imaging is an integral part of modern healthcare, further underlining the need for scientists and clinicians to be educated across disciplinary boundaries. A comprehensive competency-based curriculum has been developed with input from European experts to more effectively train cardiovascular imaging specialists. Competencies span 22 domains including an understanding of the physical principles of imaging, anatomy and physiology, pharmacology and radiopharmaceutical handling, indication, protocol and reporting, and performance of specific imaging techniques. External funding sources to create the photographic atlas for the anatomical and physiologic descriptions in the curriculum are being sought (Westwood et al., 2023).

There is an understated need to advance training outside European regions to encourage the pursuit of further educational opportunities. Educational resources and examples to aid in the development of a similar curriculum are available upon request.

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Digital tools integrated into medical practice have been shown to improve efficiency, workflow, job satisfaction, and ultimately reduce human error. With the explosion of digitalization, training to become proficient with digital tools is an increasingly vital learning objective. In addition to practical competency with digital tools, there is a need to cultivate a wider data literacy: the ability to critically assess, create, leverage, share, and store data safely while minimizing risks to oneself and society as a whole.

10. Future Directions and Emerging Technologies

Imaging biomarker development is being enhanced by multicenter initiatives, scan-rescan protocols, and deliberations on human and machine learning data utilizsation to improve generalisability and precision (Seetharam et al., 2020). Cardiac magnetic resonance automated scar quantification and artificial intelligence disease-feature extraction for pulmonary arterial hypertension constitute current projects under these auspices. A concomitant precision medicine-collaborative effort aims to integrate genetic profiling and clinical imaging within pulmonary arterial hypertension; cardiopulmonary-ventilation imaging and tissue-tracking artificial intelligence models enhance prediction of cardiac-remodelling and myofibrosis variables even without contrast-agent administration. Digital twins and mobile technology are synergising to fuel progressive avenues toward personalised-healthcare frameworks and cardiovascular-disease digitisation. Artificial intelligence is poised to transform clinical-trial orchestration and refine therapeutic strategies such as cardiac-resynchronisation therapies.

Technological-ripple effects are anticipated to elicit proactive research-question formulation and targeted investment across an expanded fractional cross-section of personalised imaging, cardiogenic and genomics-data integration, and AI-based predictive, procedural, or prognostic anatomy (Pepe et al., 2023). A comprehensive suite of imaging strategies remains in quotidian use, with every modality undergoing evolution on multiple fronts and cumulative refinement. Emerging imaging-likelihood magnitudes highlight clinical potential facilitated by vast patient cohorts seeking incremental gains; advances include blood-flow-velocity and regeneration-temporal assessment, retention-time quantitation, novel tracers (e.g., iron oxide, fluorocarbon, iodine-x-ray, perfusable-microencapsulated-particles, and phosphorous-metabolic). Crowd-source, scan-swap, or high-throughput-sample trials are prime examples of requisite-coordinate digital-cardio-edits, lending practicable solicitation for advance-magnitude Operation-Movements.

11. Conclusion

The digital transformation of society has fundamentally altered communication and information processing. In the field of healthcare, this transformation is significantly changing the modalities of patient care, the process of patient workup, the nature of

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healthcare delivery, and the organization of healthcare systems. Cardiac imaging is a critical component of the overall management of cardiovascular disease, which is the number one cause of premature morbidity and mortality worldwide. The growing demand for cardiac imaging is requiring rethinking of the organization of cardiac imaging care, and how to effectively incorporate into practice the multitude of technological developments accompanying this new era in cardiovascular healthcare.

Healthcare organizations are undertaking fundamental redesign of care delivery processes. The implementation of the lean methodology (also known as the Toyota production system) has gained significant interest within a number of healthcare organizations. The widespread adoption of the lean methodology by other industries has inspired and facilitated its entry into the healthcare setting. This methodology is centered on a novel understanding of value delivery to customers—identified as improving health, comfort, and convenience. Specific undertaking's include defining the customer (the patient) and the value proposition (cardiac imaging), detailing the entire set of actions involved with delivering that value proposition, identifying value-adding actions and non-value-adding or inefficient actions, striving for a balanced workflow, and seeking to minimize or eliminate the latter class of actions.

Healthcare organizations are also investigating ways in which care delivery can be made more multidisciplinary, acknowledging that greater collaboration among the various professional players involved actually enhances overall service delivery to the customer or patient. Interdepartmental operating characteristics and performance metrics are also being redefined in support of this vision. Additional opportunities exist for further broadening interprofessional collaboration in cardiac imaging organizations, where engaging with specialized allied health personnel representing fields such as pharmacy, informatics, information technology and computer science, and echocardiography would enhance digital transformation across multiple fronts.

Coordination of services between diagnostic imaging and nuclear medicine or radiology and interventional cardiology serves as an example of current interdepartmental multidisciplinary collaboration. Substantial prospect remain for extending these arrangements in support of digital transformation. These services help cardiologists evaluate the safety of conducting imaging and stress testing procedures in the same appointment, provide second opinions when needed or desired, offer recommendations on alternative imaging modalities and pharmacological agents that could supplement specific investigations, and give input concerning the use of advanced machine-learning tools capable of extracting quantitative measurements from imaging studies.

Widespread adoption of digital technology for service entry, performance documentation, tool configuration, camera initialization, and image access underscores the value of engaging additional allied health personnel. Many cardiologists recording requisitions on paper still

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ISSN:1000-3673
Received: 06-02-2025 *Revised: 15-03-2025* *Accepted: 11-04-2025*

lack facility with the extensive array of specialized software and hardware linked with cardiac imaging. Knowledgeable experts could thereby expedite the dementia-free completion of computerized information and assist in selecting optimal settings that minimize the turnaround time necessary to configure these tools. A detailed assessment of current status, capabilities, and professional relationships is required to inform the elaboration and transformation of patient pathways, care delivery configurations, and digitalization opportunities within cardiac imaging organizations.

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