Journal of sustainable food, water, energy and environment

The applications of X-ray technology in medical imaging: advances, challenges, and future perspectives (A review)

*Abdalrahman M. Rayan[1,] *, Ahmed Adam[2], Gehad Al-Arabi[3], and Mahrous R. Ahmed[1]*

[1]Physics Department, Faculty of Science, Sohag University, Sohag 82524, Egypt

[3]Botany and microbiology Department, Faculty of Science, Sohag University, Sohag 82524, Egypt

[2]Urology Department, Faculty of Medicine, Sohag University, Sohag 82524, Egypt

Received: 11 June. 2025, Revised: 24 Aug. 2025, Accepted: 25 Aug. 2025 Published online 24 Sep. 2025

Abstract: In 1895, Wilhelm Conrad Röntgen (1845–1923) pioneered X-ray imaging, which revolutionized medical diagnosis and modern healthcare. X-ray imaging's fundamentals, therapeutic uses, technology advances, and future directions are examined in detail. X-rays contrast bone and soft tissues by attenuation, absorption, and scattering. X-ray medical usage. In diagnostic radiography, it is best for fracture diagnosis, chest pathology, including pneumonia, lung cancer, and dental checks. Angiography, catheter insertion, and GI (gastrointestinal issues) diagnostics benefit from real-time dynamic fluoroscopy. Early breast cancer detection is improved by mammography, especially DBT (Digital breast tomosynthesis). Cross-sectional X-ray imaging using multi-slice contrast-enhanced CT (Computed Tomography). Fast, inexpensive, non-invasive, good spatial resolution for osseous structures, and widely available in healthcare, X-ray imaging. These benefits are negated by ionizing radiation dangers (requiring rigorous ALARA (As Low as Reasonably Achievable) standards), worse soft-tissue contrast compared to MRI (magnetic resonance imaging) or ultrasound, limited 3D visualization without CT, and technical challenges in obese or anatomically complex patients. Technological advances alter X-rays. Digital radiography has enhanced image quality, workflow efficiency, and fracture and pneumonia screening accuracy using AI. Low-dose imaging, especially in kids, and portable critical care point-of-care technology advances. Photon-counting CT, phase-contrast imaging, and dark-field X-rays will depict soft tissues like never before, while AI (Artificial Intelligence) will speed up and improve diagnosis. Reduced doses optimize X-ray risk-benefit ratios. X-rays' efficiency, accessibility, and diagnostic ability make them crucial in medicine, even as other imaging technologies emerge. This study emphasizes the necessity for ongoing innovation to overcome limitations and preserve precision medicine benefits. X-ray imaging will remain vital to medical diagnostics with improved technology and safety precautions.

Keywords: X-ray imaging; radiography; computed tomography; medical diagnostics; radiation safety; and artificial intelligence

Abbreviations:

- GI gastrointestinal issues
- DBT (Digital breast tomosynthesis)
- CT (Computed Tomography)
- ALARA As Low as Reasonably Achievable
- MRI magnetic resonance imaging
- AI Artificial intelligence
- kVp kilovolt age peaks
- TB tuberculosis
- CAD computer-aided detection
- CCD Charge-Coupled Device
- CMOS Complementary Metal-Oxide-Semiconductor
- CBCT Cone-beam computed tomography
- ANB (Angle of point A, Nasion, and point B)
- ABC Automatic Brightness Control
- fps frames per second
- CVC Central venous catheter
- LIH last-image-hold
- SFM screen-film mammography
- FFDM full-field digital mammography
- mGy Mille gray
- DMIST Digital Mammographic Imaging Screening Trial
- ACR The American College of Radiology
- DBT Digital Breast Tomosynthesis
- CDR cancer detection rates
- C-View™ is a Hologic software that generates synthesized 2D images from 3D mammography data, specifically tomosynthesis scans
- CEM Contrast-enhanced mammography
- PCDs Photon-counting detectors
- MSCT Multi-Slice Computed Tomography
- CECT contrast-enhanced Computed Tomography

* Corresponding author E-mail: muhmedabdalrahman912@gmail.com Print ISSN 3062-5513 Online ISSN 3062-5521

- MPR Multiplanar reconstructions
- MIP maximum intensity projections
- RECISTResponse Evaluation Criteria in Solid Tumors
- DECT Dual-energy Computed Tomography
- The TNM classification It's a classification is a globally recognized system for classifying the extent of cancer spread in solid tumors. It stands for Tumor, Node, and Metastasis
- The ASPECTS Alberta Stroke Program Early CT Score) is a 10-point scoring system used to assess the extent of early ischemic changes in the brain, particularly in patients with suspected acute ischemic stroke
- IR Iterative reconstruction
- DR digital radiography
- PACS Picture archiving and communication systems
- The LNT The linear no-threshold
- BEIR VII report refers to Health Risks from Exposure to Low Levels of Ionizing Radiation
- DQE quantum detection efficiency
- AUC achieving area-under-the-curve
- CADx computer-aided diagnosis
- MBIR model-based iterative reconstruction
- VAP ventilator-associated pneumonia
- AEC automatic exposure control
- Wireless DICOM transmission the process of sending and receiving medical images and related data, adhering to the Digital Imaging and Communications in Medicine (DICOM) standard, over a wireless network
- CNNs convolutional neural networks
- NLP Natural language processing
- PACS in picture archiving and communication systems
- EID energy-integrating detector
- PCI phase-contrast imaging
- DFI dark-field imaging

1. Introduction

The discovery of X-rays in 1895 by Wilhelm Conrad Röntgen marked a revolutionary milestone in both physics and medicine [1-4]. While experimenting with cathode rays in his laboratory at the University of Würzburg, Röntgen observed an unexpected phenomenon: a fluorescent screen in his lab glowed despite being shielded from visible light. He deduced that an invisible, highly penetrating form of radiation was responsible, termed "X-rays" (X for unknown) [5]. His systematic experiments, including the iconic image of his wife Anna Bertha's hand, revealing bones and her wedding ring, demonstrated the technology's potential to visualize internal structures non-invasively.

By 1896, X-rays were already being used clinically to locate fractures and foreign objects, earning Röntgen the first Nobel Prize in Physics (1901) [4, 6]. The rapid adoption of X-rays transformed medical diagnostics [7-9], replacing invasive methods and guesswork with precise anatomical imaging. Over time, advancements such as digital radiography [10-13], computed tomography (CT) [14-17] and fluoroscopy [18-20] expanded their applications from detecting tuberculosis to guiding surgical procedures. However, early use also revealed risks, including radiation burns and cancer [21-24], leading to the development of safety protocols (e.g., ALARA principle) [25-28]. Today, X-rays remain indispensable in emergency medicine, oncology, and dentistry, while ongoing innovations—like AI-assisted interpretation and low-dose techniques—address their limitations [29-31]. As we reflect on Röntgen's legacy, X-ray imaging continues to evolve, balancing diagnostic power with patient safety in modern healthcare.

X-rays remain a cornerstone of modern medical diagnostics due to their unparalleled ability to non-invasively visualize internal anatomical structures with high resolution and rapid acquisition. Since its discovery in 1895, X-ray imaging has become indispensable across multiple medical specialties, including radiology, orthopedics [32-34], pulmonology [35-37], dentistry [38-40], and emergency medicine [41, 42]. Their primary utility lies in the detection of fractures, dislocations, and degenerative bone diseases, where their high spatial resolution allows for the precise assessment of skeletal integrity. In chest radiography, X-rays serve as a first-line diagnostic tool for identifying pulmonary pathologies such as pneumonia [43, 44], tuberculosis [45-47], pleural effusions [48-50], and malignancies [51], often guiding further investigations like CT or biopsy. Additionally, dental radiography is critical for diagnosing caries, periodontal disease, and impacted teeth, while mammography plays a vital role, significantly improving patient outcomes through early intervention [52-56]. Beyond static imaging, fluoroscopy enables real-time dynamic assessment, facilitating complex procedures such as angiography, catheter placements, and gastrointestinal studies [20, 57, 58]. Despite the advent of advanced modalities like MRI [59, 60] and ultrasound [61, 62], X-rays retain widespread use due to their cost-effectiveness, accessibility, and rapid turnaround time, making them particularly valuable in emergency and resource-limited settings. However, the ionizing nature of X-rays necessitates strict adherence to radiation safety protocols to minimize patient and occupational exposure risks [63, 64]. Ongoing advancements, including digital radiography, AI-assisted image analysis, and low-dose techniques, continue to enhance diagnostic accuracy while mitigating radiation hazards. Thus, X-rays remain an irreplaceable tool in modern medicine, balancing diagnostic efficacy, efficiency, and safety in clinical practice.

Figure 1: Anna Bertha's hand, where the wedding ring appears in her hand [1]

By 1896, X-rays were already being used clinically to locate fractures and foreign objects, earning Röntgen the first Nobel Prize in Physics (1901) [4, 6]. The rapid adoption of X-rays transformed medical diagnostics [7-9], replacing invasive methods and guesswork with precise anatomical imaging. Over time, advancements such as digital radiography [10-13], computed tomography (CT) [14-17] and fluoroscopy [18-20] expanded their applications from detecting tuberculosis to guiding surgical procedures. However, early use also revealed risks, including radiation burns and cancer [21-24], leading to the development of safety protocols (e.g., ALARA principle) [25-28]. Today, X-rays remain indispensable in emergency medicine, oncology, and dentistry, while ongoing innovations—like AI-assisted interpretation and low-dose techniques—address their limitations [29-31]. As we reflect on Röntgen's legacy, X-ray imaging continues to evolve, balancing diagnostic power with patient safety in modern healthcare.

X-rays remain a cornerstone of modern medical diagnostics due to their unparalleled ability to non-invasively visualize internal anatomical structures with high resolution and rapid acquisition. Since its discovery in 1895, X-ray imaging has become indispensable across multiple medical specialties, including radiology, orthopedics [32-34], pulmonology [35-37], dentistry [38-40], and emergency medicine [41, 42]. Their primary utility lies in the detection of fractures, dislocations, and degenerative bone diseases, where their high spatial resolution allows for the precise assessment of skeletal integrity. In chest radiography, X-rays serve as a first-line diagnostic tool for identifying pulmonary pathologies such as pneumonia [43, 44], tuberculosis [45-47], pleural effusions [48-50], and malignancies [51], often guiding further investigations like CT or biopsy. Additionally, dental radiography is critical for diagnosing caries, periodontal disease, and impacted teeth, while mammography plays a vital role, significantly improving patient outcomes through early intervention [52-56]. Beyond static imaging, fluoroscopy enables real-time dynamic assessment, facilitating complex procedures such as angiography, catheter placements, and gastrointestinal studies [20, 57, 58]. Despite the advent of advanced modalities like MRI [59, 60] and ultrasound [61, 62], X-rays retain widespread use due to their cost-effectiveness, accessibility, and rapid turnaround time, making them particularly valuable in emergency and resource-limited settings. However, the ionizing nature of X-rays necessitates strict adherence to radiation safety protocols to minimize patient and occupational exposure risks [63, 64]. Ongoing advancements, including digital radiography, AI-assisted image analysis, and low-dose techniques, continue to enhance diagnostic accuracy while mitigating radiation hazards. Thus, X-rays remain an irreplaceable tool in modern medicine, balancing diagnostic efficacy, efficiency, and safety in clinical practice.

This review aims to provide a comprehensive analysis of the applications, benefits, limitations, and emerging trends in X-ray-based medical imaging, synthesizing current knowledge to inform clinical practice and future research. First, it examines the diagnostic and therapeutic applications of X-ray technology, including its pivotal role in radiography, fluoroscopy, computed tomography (CT), and interventional procedures. By evaluating these applications, the review highlights how X-rays facilitate rapid and accurate diagnoses in trauma, pulmonary diseases, dental disorders, and oncological imaging. Second, the discussion focuses on the advantages of X-ray imaging, such as its cost-effectiveness, widespread availability, and real-time imaging capabilities, which make it indispensable in emergency and primary care settings. However, the review also critically addresses the limitations of X-ray technology, particularly its reliance on ionizing radiation, which poses inherent risks of carcinogenesis and necessitates stringent radiation protection measures. Additionally, challenges such as limited soft-tissue contrast and overlapping anatomical structures are analysed in comparison to alternative modalities like MRI and ultrasound. Finally, the review explores future trends aimed at overcoming these limitations, including advancements in low-dose imaging techniques, artificial intelligence (AI)-enhanced diagnostics, and next-generation technologies such as phase-contrast and photon-counting CT. By integrating recent research and technological developments, this review seeks to provide a balanced perspective on the evolving role of X-rays in modern medicine, ultimately contributing to evidence-based decision-making for clinicians, researchers, and policymakers. Through this analysis, the review underscores the need for continued innovation to optimize diagnostic accuracy while minimizing risks, ensuring that X-ray technology remains both effective and safe in an era of precision medicine.

2. Discussion

2.1. Principles of X-Ray Imaging

X-rays are produced through the rapid deceleration of high-energy electrons (bremsstrahlung radiation) or electron transitions within inner atomic shells (characteristic radiation), typically within an X-ray tube. When a high-voltage potential is applied between the cathode and anode, thermionically emitted electrons are accelerated toward a tungsten target, where their sudden deceleration converts kinetic energy into X-ray photons [65, 66]. The resulting X-ray spectrum consists of a continuous bremsstrahlung spectrum superimposed with discrete characteristic peaks, dependent on the anode material and tube voltage [67, 68].

As X-rays traverse biological tissues, their interaction occurs primarily through photoelectric absorption and Compton scattering [70, 71], with relative probabilities dictated by photon energy and tissue atomic number. Photoelectric absorption, dominant at lower energies (<30 keV) and in high-Z materials like bone, results in complete photon attenuation and contributes to high-contrast imaging. In contrast, Compton scattering, prevalent at higher energies and in soft tissues, involves partial energy transfer to outer-shell electrons, generating scattered radiation that degrades image quality. A minor contribution from coherent (Rayleigh) scattering also occurs, though it does not deposit energy in tissues [72]. The differential attenuation of X-rays across tissues, owing to variations in density and atomic composition, forms the basis of radiographic contrast, enabling the visualization of anatomical structures. Modern imaging systems optimize these interactions through techniques such as beam filtration, grid use for scatter reduction, and energy-selective detection [73]. Understanding these fundamental principles is critical for optimizing diagnostic image quality while minimizing patient radiation exposure in clinical practice. Here, we will discuss the three main processes that happen during X-ray imaging. The major process is the Attenuation. It is the overarching term for the overall reduction in the intensity of the X-ray beam. When X-ray photons travel through matter (like human tissue), some of them are stopped or deflected, and the beam becomes weaker. Attenuation is not a single process; rather, it is the combined result of two phenomena, which are absorption and scattering. The attenuation process depends on the photon energy, material density, and atomic number (Z) of the absorbing medium. Attenuation determines radiographic contrast, as differential attenuation between tissues (e.g., bone vs. muscle) creates the image [74-76]. Now, interpreting the two processes which involved in attenuation:

I. Absorption (photoelectric effect) occurs when an X-ray photon transfers all its energy to an inner-shell electron, ejecting it (creating a photoelectron) and leaving a vacancy filled via characteristic radiation or Auger electrons [77, 78]. This process dominates at lower energies (<30 keV) and in High-Z materials (e.g., bone, iodine), contributing to high-contrast imaging but increasing patient dose.

II. Scattering involves partial energy transfer to the medium. Two key types are:

1. Compton scattering: The X-ray photon deflects off an outer-shell electron, losing some energy and changing direction. This dominates at higher energies (>60 keV) and in low-Z tissues (e.g., soft tissue), degrading image quality by producing scatter noise [79-82].

2. Coherent (Rayleigh) scattering: The photon is elastically scattered without energy loss, minimally affecting imaging [83, 84].

Radiographic contrast arises from differential X-ray attenuation between adjacent tissues, primarily governed by variations in tissue density, atomic number (Z), and thickness. This contrast mechanism enables the visualization of anatomical structures, with bone and soft tissue representing two extremes of radiographic differentiation.

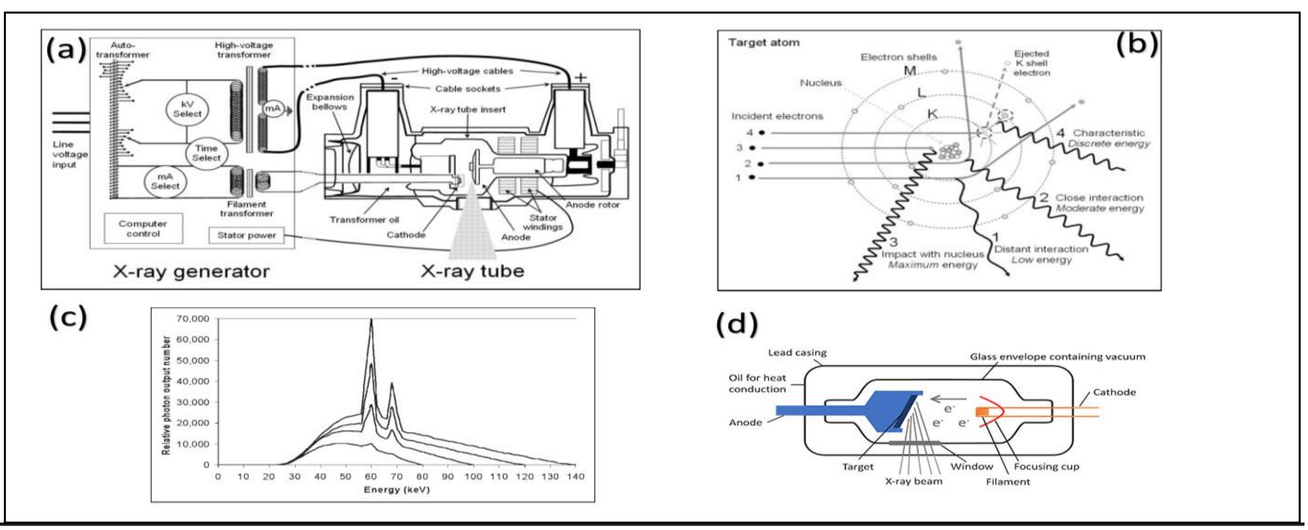

Fig. 2: The production of X-rays. (a) This figure investigates the schematic setup of the apparatus used to generate X-rays. (b) describes the atomic interaction of X-rays with the inner shells of the heavy metal atom, where it's obvious that when the electrons hit the deeper shells, high-energy X-rays are produced. (c) The X-ray spectrum is a relation between the intensity and the applied energy between the cathode and the anode. The sharp peaks that illustrate the intrinsic wavelength used in imaging or diffraction techniques. (d) a portrayal of the X-ray tube. Figures (a), (b), and (c) are taken from the reference [69]. Image (d) has been taken from the radiology café website.

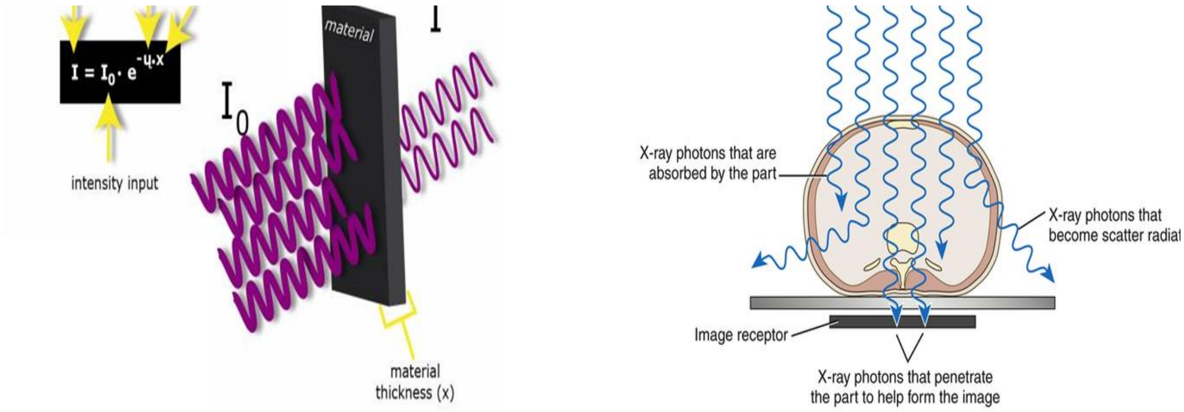

Fig. 3: (a) The attenuation process in X-ray imaging, and (b) Absorption and scattering during imaging.

2.2. Bone Imaging

Bone exhibits high radiographic contrast due to its elevated effective atomic number (Z~13) from calcium (Z=20) and phosphorus (Z=15) and greater physical density (~1.9 g/cm³). These properties enhance photoelectric absorption, particularly at lower kilovolt age peaks (kVp, typically 50-70 kVp for extremities). The significant attenuation difference between bone and surrounding soft tissues produces high-contrast images ideal for:

- Fracture detection [85, 86].
- Joint space evaluation [87].
- Skeletal abnormality assessment [88, 89].

2.3. Soft Tissue Imaging

Soft tissues (muscle, fat, organs) demonstrate lower inherent contrast due to [90, 91]:

•Similar effective Z (~7.4) and density (~1.0 g/cm³) among different soft tissues

•Compton scattering dominance at diagnostic energy ranges

•Minimal photoelectric absorption differences

Fig. 4: (a) Fracture detection. (b) Joint space evaluation, and (c) Skeletal abnormality assessment

Specialized techniques enhance soft tissue visualization:

•Mammography: Uses low kVp (25-35) to maximize photoelectric differences between fibro- glandular (Z~7.4) and adipose (Z~6.3) tissues [52, 92].

•Dual-energy subtraction: Exploits Z-dependent attenuation at different energies to separate overlapping structures [93, 94].

•Contrast agents: Introduce high-Z elements (e.g., iodine, barium) to create artificial contrast in angiography or gastrointestinal studies [95, 96].

Technical Considerations:

- kVp selection: Lower kVp increases photoelectric effect, enhancing bone contrast but increasing dose
- Scatter reduction: Grids or air gaps improve contrast by removing Compton-scattered photons
- Detector dynamic range: Modern digital systems can display both high-contrast (bone) and low-contrast (soft tissue) features simultaneously

The fundamental trade-off between contrast and radiation dose continues to drive technological advancements, including phase-contrast imaging and photon-counting detectors that promise improved soft tissue differentiation while maintaining bone visualization capabilities.

3. Clinical Applications of X-ray Imaging

3.1. Diagnostic Radiography in Fracture Detection

Diagnostic radiography remains the gold standard for fracture detection due to its ability to provide high-resolution anatomical images of bones and joints with rapid acquisition times [97]. The physical basis for fracture visualization lies in the differential attenuation of X-rays by bone tissue, which contains calcium phosphate (effective atomic number, Z~13.8) and exhibits significantly greater photoelectric absorption compared to surrounding soft tissues (Z~7.4). Standard protocols typically employ kilovoltage peaks (kVp) between 50-70 for extremities and 70-90 for larger joints, optimizing the trade-off between contrast resolution and radiation dose. At least two orthogonal projections (anteroposterior and lateral) are acquired to enable three-dimensional localization of fracture lines, with additional oblique or specialized views (e.g., Mortise view for ankle fractures) employed when clinically indicated.

Modern digital radiography systems have enhanced fracture detection sensitivity through advanced post-processing algorithms that allow simultaneous optimization of contrast and spatial resolution. Features such as edge enhancement [98] and dynamic range compression improve visualization of subtle fracture lines [99], trabecular disruptions [100], and cortical step-offs [101]. The modality demonstrates particular efficacy in detecting complete fractures (evident as radiolucent lines with irregular margins), comminated fractures (characterized by multiple bone fragments), and impacted fractures (showing areas of increased density). However, challenges persist in identifying occult fractures, especially in osteoporotic bone or anatomically complex regions like the scaphoid or femoral neck, where additional imaging with computed tomography or magnetic resonance imaging may be required.

The clinical utility of radiographic fracture assessment extends beyond initial diagnosis to include the evaluation of fracture alignment, healing progression, and potential complications such as malunion or osteomyelitis [102]. Recent advancements, including artificial intelligence-assisted fracture detection systems, have demonstrated promising results in improving diagnostic accuracy, particularly for inexperienced readers. Nevertheless, the fundamental principles of radiographic interpretation, understanding normal anatomy, recognizing fracture patterns, and correlating imaging findings with clinical presentation remain essential for optimal patient management in musculoskeletal trauma [103].

3.2. Chest X-rays in Pulmonary Pathologies (Pneumonia, Tuberculosis, Lung Cancer)

Chest radiography remains a fundamental diagnostic tool for evaluating pulmonary pathologies [104], including pneumonia [105, 106], tuberculosis (TB) [107], and lung cancer [108, 109], owing to its accessibility, cost-effectiveness, and rapid acquisition time. The inherent contrast between air-filled lungs (low attenuation) and pathological consolidations or masses (higher attenuation) enables the detection of key radiographic signs.

In pneumonia, chest X-rays reveal lobar or segmental consolidations with air Broncho-grams, typically appearing as homogenous opacities in bacterial infections, while interstitial patterns suggest viral or atypical pathogens. Tuberculosis manifests with diverse radiographic features: primary TB often presents with hilar lymphadenopathy and pleural effusions, whereas post-primary (reactivation) TB demonstrates apical cavitations, fibro nodular infiltrates, and miliary patterns in disseminated cases. For lung cancer, chest radiographs may detect solitary pulmonary nodules (>1 cm), hilar masses, or peripheral lesions with spiculated margins, though sensitivity is limited for small (<1 cm) or centrally located tumours [110, 111].

Despite its utility, chest radiography has limitations, including reduced sensitivity for early-stage malignancies and ground-glass opacities, often necessitating confirmatory CT imaging [113, 114]. Advances such as dual-energy subtraction and computer-aided detection (CAD) systems have improved diagnostic accuracy [115, 116], particularly in TB-endemic regions and lung cancer screening. Nevertheless, chest X-rays remain indispensable for initial evaluation, treatment monitoring, and follow-up of pulmonary diseases, balancing diagnostic efficacy with minimal radiation exposure.

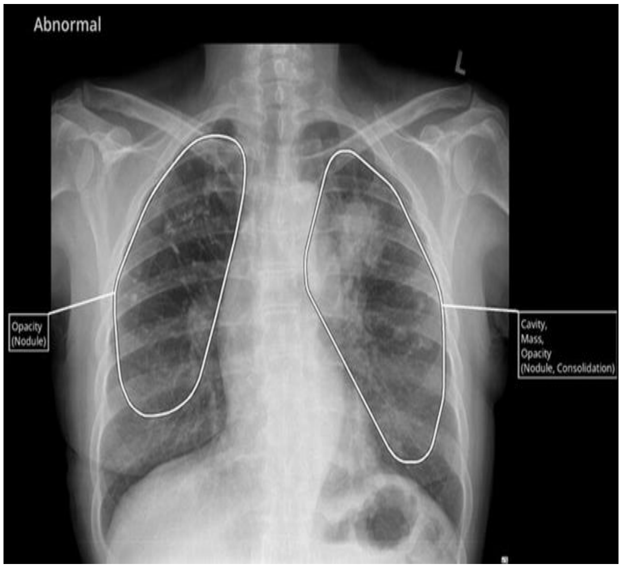

Fig. 5: An example of a chest radiograph of a patient with lung cancer [112].

3.3. Dental Radiography in Caries Detection and Orthodontic Management

Dental radiography serves as an essential diagnostic tool in modern dentistry [117, 118], enabling the detection of caries (tooth decay) and facilitating comprehensive orthodontic assessment through high-resolution imaging of dental and maxillofacial structures. The modality leverages differential X-ray attenuation between enamel (high mineral content, Z=13-15), dentin (intermediate attenuation), and carious lesions (reduced density), producing detailed images of tooth morphology and pathology [119, 120].

3.3.1 Caries Detection

Intraoral radiographs, particularly bitewing and periapical views, are the gold standard for identifying interproximal and occlusal caries that may evade visual examination. Early caries appears as radiolucent zones in enamel or dentin, while advanced lesions extend toward the pulp chamber. Digital radiography (using CCD (Charge-Coupled Device) / CMOS (Complementary Metal-Oxide-Semiconductor) sensors) enhances detection sensitivity through image enhancement algorithms, reducing radiation exposure by 50-80% compared to conventional film. Cone-beam computed tomography (CBCT) may be employed for complex cases, providing a 3D evaluation of caries extent and proximity to vital structures.

3.3.2 Orthodontic Applications

Dental radiographs play a pivotal role in orthodontic diagnosis and treatment planning:

1.Panoramic radiography assesses overall dentition, eruption patterns, and jaw relationships [121].

2.Cephalometric radiography quantifies skeletal-dental relationships (e.g., ANB (Angle of point A, Nasion, and point B) angle for malocclusion classification. [122].

3.Periapical/occlusal views evaluate root alignment and bone support prior to brace placement [123].

Emerging technologies like AI-assisted caries detection and low-dose CBCT are refining diagnostic precision while minimizing radiation risks. Nevertheless, the ALARA principle remains critical, particularly for paediatric patients requiring longitudinal monitoring.

4.Fluoroscopy: Principles and Clinical Applications in Real-Time Imaging

Fluoroscopy represents a dynamic radiographic imaging modality that enables real-time visualization of internal structures, making it indispensable for gastrointestinal (GI) studies, angiography, and catheter-guided interventions [124]. Unlike conventional radiography, which captures static images, fluoroscopy employs a continuous or pulsed X-ray beam coupled with an image intensifier or digital detector system to produce live, high-temporal-resolution imaging. This technology operates on the same fundamental principles of X-ray attenuation as standard radiography but incorporates advanced features such as automatic brightness control (ABC) and pulse-rate modulation to optimize image quality while managing radiation dose [20, 125, 126].

4.1 Gastrointestinal Studies

Fluoroscopic evaluation of the GI tract, including barium swallows, upper GI series, and small bowel follow-throughs, relies on the administration of radiopaque contrast agents (e.g., barium sulphate or water-soluble iodinated compounds) to delineate mucosal surfaces and luminal patency. Real-time imaging captures functional dynamics, such as esophageal motility disorders (e.g., achalasia), gastric emptying delays, or intestinal obstructions, with a typical frame rate of 3–30 frames per second (fps). Double-contrast techniques, combining barium and air, enhance sensitivity for detecting mucosal lesions (e.g., ulcers or early-stage neoplasms). The integration of digital subtraction fluoroscopy further improves lesion conspicuity by eliminating overlapping bone shadows [127-129].

4.2 Angiography and Vascular Interventions

In diagnostic and interventional angiography, fluoroscopy guides catheter navigation through vascular systems while administering iodinated contrast to visualize blood flow and detect pathologies such as stenoses, aneurysms, or arteriovenous malformations [130, 131]. Key applications include:

•Coronary angiography: Evaluates atherosclerotic plaques with submillimetre spatial resolution.

•Peripheral angiography: Assesses limb perfusion in critical ischemia.

•Micro angiography: Diagnoses cerebral aneurysms or strokes.

Modern systems employ road-mapping techniques, where a baseline angiogram is superimposed on live fluoroscopy to aid catheter manipulation, reducing procedure time and contrast load.

4.3 Catheter Placement and Guided Procedures

Fluoroscopy is the cornerstone of minimally invasive interventions, including:

•Central venous catheter (CVC) placement: This ensures correct positioning in the superior vena cava.

•Percutaneous nephrostomy: Guides renal access under real-time imaging.

•Electrophysiology studies: Maps cardiac arrhythmias during ablation procedures.

Low-dose protocols and collimation minimize scatter radiation, while last-image-hold (LIH) functions reduce unnecessary exposure.

4.4 Technological Advancements and Safety

The transition from image intensifiers to flat-panel detectors has improved spatial resolution, contrast sensitivity, and dose efficiency. Pulsed fluoroscopy reduces dose by 50–80% compared to continuous modes, and spectral shaping (e.g., copper filtration) optimizes beam quality for specific procedures. Nevertheless, stochastic radiation risks (e.g., cancer) and deterministic effects (e.g., skin injuries in prolonged interventions) necessitate strict adherence to ALARA principles. Emerging innovations like AI-enhanced noise reduction and 3D fluoroscopic navigation (e.g., cone-beam CT fusion) promise to further refine procedural accuracy.

5. Mammography: Advancements in Breast Cancer Screening – Digital Mammography versus 3D Tomosynthesis

Mammography remains the cornerstone of breast cancer screening, demonstrating proven efficacy in early detection and mortality reduction. The transition from screen-film mammography (SFM) to full-field digital mammography (FFDM) and subsequently to digital breast tomosynthesis (DBT, or 3D mammography) represents significant technological evolution, each offering distinct advantages in diagnostic accuracy, workflow efficiency, and radiation dose optimization [132, 133].

5.1 Digital Mammography (FFDM): Technical Basis and Clinical Utility

FFDM utilizes solid-state detectors, typically amorphous selenium or silicon-based, to convert X-rays into electronic signals, which are then reconstructed into high-resolution digital images. Compared to SFM, FFDM provides superior contrast resolution, particularly in dense breast tissue, and enables post-processing enhancements such as window-level adjustments, magnification, and computer-aided detection (CAD) integration. The dose efficiency of FFDM (mean glandular dose ~1.6–2.0 mGy per view) is comparable to or slightly lower than SFM, while eliminating film-processing artifacts. Large-scale trials, including the Digital Mammographic Imaging Screening Trial (DMIST), demonstrated FFDM's improved sensitivity (70–90%) over SFM, particularly in women under 50, premenopausal women, and those with heterogeneously dense or extremely dense breasts (ACR categories C/D) [134-136].

5.2 Digital Breast Tomosynthesis (DBT): Overcoming Structural Overlap

DBT addresses a fundamental limitation of conventional mammography—anatomical noise caused by tissue superposition—by acquiring multiple low-dose projections (typically 9–25) across a limited angular range (15–50°). These projections are reconstructed into 1-mm-thick slices, reducing parenchymal overlap and improving lesion conspicuity [137, 138]. Key advantages include:

•Increased cancer detection rates (CDR): Meta-analyses report a 20–40% increase in invasive cancer detection compared to FFDM alone, particularly for small (<1 cm) and spiculated masses.

•Reduced recall rates: DBT decreases false positives by 15–30%, minimizing unnecessary biopsies and follow-ups.

•Improved assessment of lesion margins and architecture, critical for BI-RADS classification.

However, DBT presents challenges, including longer interpretation times (30–50% increase) and higher radiation doses (combined FFDM+DBT ≈ 2.5–3.5 mGy). Synthetic 2D reconstructions (e.g., C-View™) mitigate dose concerns by eliminating the need for separate FFDM acquisitions.

5.3 Comparative Performance in Screening and Diagnostic Settings

•Screening populations: The TOST and Malmö trials demonstrated DBT's superiority in reducing interval cancers (HR 0.70–0.80), suggesting enhanced early detection.

•Dense breasts: DBT's sensitivity in dense tissue (85–92%) surpasses FFDM (70–80%), though supplemental modalities (e.g., ultrasound, MRI) may still be warranted for high-risk patients.

•Cost-effectiveness: While DBT requires higher initial capital investment, its reduced recall rates may lower long-term healthcare expenditures.

5.4 Emerging Innovations and Future Directions

•AI integration: Deep learning algorithms assist in micro calcification detection and risk stratification (e.g., predicting malignancy likelihood).

•Contrast-enhanced mammography (CEM): Combines iodine-based contrast with FFDM/DBT, offering MRI-like sensitivity in lesion characterization.

•Ultra-low-dose protocols: Photon-counting detectors (PCDs) promise sub-1 mGy exams without compromising image quality.

6.Computed Tomography (CT): Advancements in Cross-Sectional Imaging with Multi-Slice and Contrast-Enhanced Techniques

Computed Tomography (CT) has revolutionized diagnostic imaging by providing high-resolution, cross-sectional anatomical visualization through the integration of X-ray technology and advanced computational reconstruction algorithms. Unlike conventional radiography, which produces superimposed 2D images, CT generates sequential axial slices that can be reformatted into coronal, sagittal, or 3D volumetric images, enabling comprehensive evaluation of complex anatomical structures and pathologies. The evolution from single-slice to multi-slice CT (MSCT) and the development of contrast-enhanced CT (CECT) protocols have significantly expanded clinical applications, improving diagnostic accuracy, temporal resolution, and patient-specific optimization [139-141].

7. Multi-Slice CT (MSCT): Technological Foundations and Clinical Advantages

MSCT, introduced in the late 1990s, employs multiple detector rows (ranging from 4 to 320 slices) to simultaneously capture data during a single gantry rotation [142-144]. This innovation offers several key benefits:

1.Improved Spatial and Temporal Resolution: Modern MSCT systems achieve submillimetre isotropic resolution (0.5–0.625 mm slice thickness), critical for visualizing small structures such as coronary arteries, pulmonary nodules, or subtle fractures. High-speed gantry rotation (<0.3 seconds) reduces motion artifacts, particularly in cardiac or trauma imaging.

2.Extended Anatomical Coverage: MSCT allows rapid acquisition of large volumes (e.g., whole-body trauma scans in <10 seconds), minimizing patient movement and breath-holding requirements.

3.Advanced Post-Processing Capabilities: Multiplanar reconstructions (MPR), maximum intensity projections (MIP), and volume-rendered images enhance diagnostic interpretation in vascular, orthopedic, and oncological imaging.

7.1 Contrast-Enhanced CT (CECT): Mechanisms and Diagnostic Utility

CECT utilizes intravenous (IV) iodinated contrast media to augment tissue contrast, leveraging differences in vascularity and perfusion between normal and pathological tissues [145, 146]. The timing of image acquisition relative to contrast administration is categorized into distinct phases:

•Non-Contrast CT: Baseline assessment of calcifications, hemorrhage, or fat-containing lesions (e.g., adrenal adenomas).

•Arterial Phase (20–30 sec post-injection): Optimal for hyper-vascular lesions (e.g., hepatocellular carcinoma, hyper-enhancing renal masses) and arterial anatomy (e.g., pulmonary embolism, aortic dissection).

•Portal Venous Phase (60–70 sec): Standard for most abdominal evaluations, including liver metastases, pancreatic tumours, and venous thrombosis.

•Delayed Phase (3–5 min): Useful for excretory phase urography or fibrotic tissue characterization.

CECT is indispensable for tumour staging (e.g., RECIST criteria), vascular pathology (e.g., aneurysms, stenoses), and inflammatory conditions (e.g., abscesses, pancreatitis). Dual-energy CT (DECT), an advanced CECT technique, exploits material decomposition algorithms to differentiate iodine, calcium, or uric acid, enabling virtual non-contrast imaging and reducing overall radiation exposure.

8. Clinical Applications and Evidence-Based Outcomes

•Oncology: MSCT with CECT is the backbone of cancer staging (TNM classification), assessing tumour size, lymph node involvement, and distant metastases. Perfusion CT quantifies tumour vascularity, predicting treatment response in glioblastomas or colorectal liver metastases.

•Cardiovascular Imaging: Coronary CT angiography (CCTA) with MSCT detects atherosclerotic plaques with >95% sensitivity, while ECG-gated acquisitions evaluate cardiac function and valve morphology.

•Neuroimaging: Non-contrast CT remains first-line for acute stroke (ASPECTS score), while CECT identifies vascular malformations or tumoral enhancement.

•Trauma: Whole-body MSCT ("pan-scan") is the standard for polytrauma, diagnosing life-threatening injuries (e.g., splenic laceration, pneumothorax) with >90% sensitivity.

8.1 Dose Optimization and Future Directions

Despite its diagnostic power, CT contributes significantly to medical radiation exposure. Strategies to mitigate dose include:

•Iterative reconstruction (IR) and AI-based de-noising algorithms, reducing dose by 30–60% without compromising image quality.

•Protocol personalization based on body habitus and clinical indication (e.g., low-dose lung cancer screening at 1–2 mSv).

•Photon-counting CT (PCCT), an emerging technology offering superior spatial resolution and spectral imaging at reduced doses.

9. Advantages of X-ray Imaging

9.1 Speed and cost-effectiveness

X-ray imaging remains a cornerstone of diagnostic radiology due to its unparalleled speed and cost-effectiveness, making it indispensable in both emergency and routine clinical settings. The acquisition of conventional radiographs typically requires less than 1 second per exposure, enabling rapid assessment of critical conditions such as fractures, pneumothoraces, or bowel obstructions. This efficiency is particularly vital in high-volume environments like emergency departments, where time-sensitive decisions rely on immediate imaging results. Furthermore, modern digital radiography (DR) systems eliminate the need for film processing, reducing examination times to under 5 minutes from image capture to interpretation. Compared to advanced modalities such as MRI or CT, which may require 15–60 minutes per study, X-rays offer a decisive advantage in workflow optimization, particularly for triaging unstable patients [147].

From an economic standpoint, X-ray imaging is a highly resource-efficient diagnostic modality. The initial capital outlay and ongoing operational expenses for radiographic systems are considerably lower than those for cross-sectional modalities such as MRI or CT. For instance, portable X-ray units typically cost between $50,000 and $100,000, which is a fraction of the $1-2 million required for an MRI or CT scanner. This cost-effectiveness, coupled with high diagnostic accuracy for common indications like fracture and pneumonia detection, underscores its significant value. The judicious application of X-rays, guided by evidence-based protocols, ensures optimal resource allocation and strong clinical outcomes, cementing its role as a foundational, cost-effective tool in modern medicine.

9.2 High Spatial Resolution for Bone Structures

X-ray imaging is unparalleled in its ability to provide high spatial resolution for visualizing bone structures, making it the gold standard for diagnosing skeletal pathologies. The modality achieves spatial resolutions of 0.1–0.2 mm, enabling the detection of fine anatomical details such as trabecular patterns, micro fractures, and cortical disruptions that may be imperceptible with other imaging techniques. This precision stems from the differential attenuation of X-rays by calcium-rich bone tissue (effective atomic number, $Z \approx 13.8$), which absorbs photons more efficiently than soft tissues ($Z \approx 7.4$), producing exceptional contrast between osseous and non-osseous structures. As a result, radiographs can delineate subtle fractures, such as hairline fissures in the scaphoid or occult hip fractures, with high diagnostic confidence, guiding timely clinical interventions [51, 147].

The superior resolution of X-rays is particularly evident in extremity and joint imaging, where intricate anatomical relationships must be preserved. For instance, standard hand or wrist radiographs can reveal early erosions in rheumatoid arthritis or subperiosteal resorption in hyperparathyroidism, features critical for disease staging. Similarly, dental radiography leverages this capability to identify periapical abscesses, root fractures, and periodontal bone loss with micron-level precision. Even in comparison to advanced modalities like CT, conventional radiography often provides sharper edge definition for cortical bone evaluation, albeit without cross-sectional capabilities.

Technological advancements, such as digital radiography (DR) with high-frequency generators, have further enhanced spatial resolution while minimizing radiation dose. Post-processing tools, including edge enhancement algorithms and magnification functions, allow radiologists to scrutinize fine bony details without additional exposures. Nevertheless, the modality's limitations in soft-tissue contrast underscore its specialized role in musculoskeletal imaging. When combined with clinical correlation, X-rays' high spatial resolution for bone structures ensures its continued dominance in fracture management, orthopedic planning, and metabolic bone disease assessment.

9.3 Non-invasive (compared to surgery)

X-ray imaging represents a fundamental non-invasive diagnostic modality that provides critical clinical information without the risks associated with surgical exploration. Unlike invasive procedures, which require tissue penetration, anesthesia, and prolonged recovery, radiography enables internal visualization through external energy application (X-ray photons) and detection of transmitted radiation, eliminating the need for incisions or physiological disruption. This non-invasiveness is particularly valuable in acute trauma evaluation, where rapid diagnosis of fractures, dislocations, or pneumothoraces must be achieved without exacerbating patient injury. For example, a simple two-view radiographic series can confirm a femoral neck fracture with >95% sensitivity, obviating the need for diagnostic arthroscopy or exploratory surgery. Similarly, chest X-rays reliably identify pleural effusions or pulmonary consolidations that might otherwise require thoracentesis or biopsy for confirmation.

The non-invasive nature of X-ray imaging also reduces procedure-related complications, including surgical site infections, hemorrhage, or anesthesia-related adverse events. In pediatric populations, where invasive procedures pose heightened risks, radiography serves as a first-line tool for diagnosing congenital hip dysplasia, scoliosis, or non-accidental injuries without subjecting children to unnecessary operative interventions. Furthermore, serial radiographic examinations allow for longitudinal monitoring of conditions such as osteomyelitis or fracture healing, providing repeated assessments without cumulative morbidity.

While advanced modalities like MRI or ultrasound also offer non-invasive alternatives, X-rays maintain distinct advantages in accessibility, speed, and cost-efficiency. Even in cases where soft-tissue evaluation is limited, the combination of radiographic findings with clinical correlation often suffices for definitive diagnosis, avoiding more invasive steps. As low-dose protocols and digital tomosynthesis continue to evolve, the non-invasive benefits of X-ray imaging are further enhanced, reinforcing its role as an indispensable diagnostic tool that balances patient safety with clinical efficacy.

9.4 Widely available in hospitals and clinics

X-ray imaging maintains a dominant position in medical diagnostics due to its near-universal availability across healthcare settings, from tertiary care hospitals to rural clinics. This ubiquity stems from several factors, including relatively low infrastructure requirements, cost-effective implementation, and operational simplicity compared to advanced imaging modalities. Unlike MRI or CT, which demand specialized shielding, cryogenic cooling, or high-power electrical systems, radiographic units can be installed in virtually any clinical space with standard radiation shielding and power supply. Portable X-ray machines further extend accessibility to bedside, emergency, and intraoperative settings, enabling immediate imaging for critically ill or immobile patients.

The widespread adoption of X-ray technology ensures equitable access to diagnostic services, particularly in resource-limited regions where advanced imaging is often unavailable. Serving as a primary tool for critical screenings and trauma evaluations, radiography helps bridge healthcare disparities globally. Even in well-equipped facilities, X-rays remain a vital first-line modality for common conditions, which reduces the burden on costlier and complex services. The technology's simplicity allows a variety of clinicians to perform and interpret basic studies, expediting time-sensitive clinical decisions. The shift to digital radiography (DR) and Picture Archiving and Communication Systems (PACS) has further enhanced this accessibility by enabling rapid image sharing for remote consultations. This, combined with low operational costs and durable hardware, makes X-ray imaging a sustainable and scalable diagnostic solution, solidifying its indispensable role in both routine and emergency care worldwide.

10. Limitations and Risks

10.1 Ionizing radiation exposure (cancer risk, ALARA principle)

Despite its diagnostic utility, X-ray imaging carries inherent risks due to ionizing radiation exposure, which has been linked to stochastic effects (e.g., carcinogenesis) and deterministic effects (e.g., tissue reactions at high doses). The linear no-threshold (LNT) model, widely adopted by regulatory bodies, posits that even low-dose exposure may incrementally increase lifetime cancer risk, particularly for pediatric patients and repeated examinations. Epidemiological studies, such as the BEIR VII report, estimate that 1 mSv of effective dose (equivalent to ~4 chest X-rays) confers a 0.005% increased lifetime risk of fatal cancer, necessitating strict adherence to the ALARA (As Low As Reasonably Achievable) principle [148].

10.2 Radiation risks are tissue- and age-dependent:

•Children exhibit heightened radio sensitivity due to rapidly dividing cells and longer post-exposure lifespans (5–10× greater risk per unit dose than adults).

•Gonadal exposure during pelvic radiography raises concerns about genetic effects, albeit with minimal evidence at diagnostic doses.

•Cumulative exposure in chronic imaging (e.g., serial scoliosis monitoring) may breach 100 mSv, approaching thresholds for measurable cancer risk.

To mitigate these risks, modern protocols emphasize:

•Dose optimization: Use of low kVp/high mAs for high-contrast exams (e.g., bone imaging) and high kVp for chest studies to reduce skin dose.

•Collimation and shielding: Thyroid shields (for dental X-rays) and lead aprons for radiosensitive tissues.

•Alternative modalities: Ultrasound or MRI for pediatric and obstetric imaging when feasible.

While the absolute risk remains small compared to clinical benefits, ongoing advancements in digital detectors, iterative reconstruction, and AI-driven dose reduction continue to refine X-ray safety.

10.3 Poor soft-tissue contrast (compared to MRI/ultrasound)

One of the most significant limitations of X-ray imaging is its poor soft-tissue contrast resolution, particularly when compared to advanced modalities such as magnetic resonance imaging (MRI) and ultrasound. This constraint arises from the fundamental physics of X-ray interactions with biological tissues, where attenuation differences between soft-tissue structures (e.g., muscles, tendons, and organs) are often minimal, resulting in low-contrast differentiation. Unlike MRI, which exploits variations in proton relaxation times to generate high soft-tissue contrast, or ultrasound, which uses acoustic impedance differences, X-ray imaging relies primarily on density and atomic number disparities, which are less pronounced in non-calcified tissues. Consequently, pathologies such as ligamentous injuries, brain parenchyma abnormalities, or early-stage tumors may remain undetectable on conventional radiographs.

The clinical implications of these limitations are significant. In neurological imaging, for instance, X-rays are unable to visualize intracranial structures, rendering them ineffective for diagnosing conditions such as strokes, gliomas, or demyelinating diseases, all of which require advanced modalities like MRI or CT for accurate assessment. Similarly, in musculoskeletal imaging, while X-rays are highly effective for detecting fractures, their poor sensitivity for non-osseous pathologies like ligament tears, meniscal injuries, or early-stage stress fractures necessitates the use of more advanced cross-sectional techniques. This limitation also extends to oncology, where X-rays are restricted to identifying advanced bony metastases and cannot characterize soft-tissue tumours, a task for which modalities like CT, MRI, or PET-CT are essential. Ultimately, despite its utility as a first-line tool, the limited soft-tissue contrast of X-ray imaging requires the use of other advanced techniques for the definitive diagnosis of many conditions. They often fail to reveal meniscal tears, rotator cuff injuries, or bone marrow edema, necessitating supplementary MRI examinations. In abdominal imaging, radiographs provide limited information about solid organ pathology (e.g., liver lesions or pancreatic masses), where ultrasound or contrast-enhanced CT is preferred.

Technological advancements like digital tomosynthesis and dual-energy subtraction have partially improved tissue differentiation in X-ray imaging, though they do not achieve the soft-tissue resolution of MRI. Efforts to enhance contrast through increased radiation dose are also constrained by the ALARA (As Low As Reasonably Achievable) principle, as higher exposure does not yield a proportional improvement in soft-tissue resolution. Consequently, while X-rays are indispensable for bone and pulmonary imaging and acute trauma, their diagnostic utility for soft-tissue applications remains limited, reinforcing the necessity of a multimodal approach for comprehensive patient care.[149].

10.4 Limited 3D visualization (unless using CT)

A fundamental constraint of conventional X-ray imaging lies in its inherent two-dimensional projection geometry, which results in limited three-dimensional visualization of anatomical structures. This limitation stems from the physical principle of superimposition, where all tissues along the X-ray beam path are compressed into a single planar image. Consequently, critical spatial relationships between structures may be obscured, potentially compromising diagnostic accuracy. The superposition effect is particularly problematic in complex anatomical regions such as the chest (where ribs may obscure pulmonary nodules), the spine (where vertebral elements overlap), and the skull (where multiple bony structures intersect). This 2D limitation contrasts sharply with computed tomography (CT), which provides true cross-sectional imaging through volumetric acquisition and reconstruction algorithms.

The clinical implications of this dimensional constraint are significant. In fracture assessment, for instance, non-displaced fractures may be missed in up to 15-20% of cases when relying solely on conventional radiography, particularly in anatomically complex areas like the scaphoid or femoral neck. Similarly, in pulmonary imaging, the sensitivity for detecting small (<1 cm) lung nodules decreases substantially compared to CT, with studies demonstrating up to 25% of potentially malignant nodules being overlooked on chest radiographs. The superimposition problem also complicates the evaluation of organ size and precise lesion localization, often necessitating additional views or follow-up imaging. While specialized techniques such as stereoscopic radiography or digital tomosynthesis attempt to address this limitation by providing pseudo-3D information, they cannot match the spatial resolution and true volumetric data acquisition of CT. The development of dual-energy subtraction radiography has provided some improvement in tissue differentiation, but fundamental 3D relationships remain challenging to ascertain. This dimensional limitation becomes particularly consequential in surgical planning, radiation therapy targeting, and complex fracture management, where precise spatial understanding is paramount. Modern solutions to this challenge include the integration of artificial intelligence (AI) algorithms to reconstruct three-dimensional information from two-dimensional projections, as well as the increased use of cone-beam computed tomography (CT) in specialized fields like dentistry and orthopedics. However, these approaches still face obstacles in widespread clinical adoption, primarily due to concerns regarding cost-effectiveness and radiation dose. Therefore, while conventional radiography remains a vital tool for initial screening, its inherent dimensional constraints often require supplemental advanced imaging for a comprehensive evaluation, especially in complex clinical cases.10.5 Challenges in obese patients or overlapping structures.

10.5 Challenges in obese patients or overlapping structures

X-ray imaging faces significant diagnostic limitations when evaluating obese patients or anatomically complex regions where structures overlap. In obese individuals, increased adipose tissue thickness results in greater X-ray attenuation and scatter radiation, which degrades image quality by reducing contrast resolution and increasing noise. The higher photon absorption in larger body habitus often necessitates increased technical parameters (e.g., higher kVp and mAs), leading to elevated radiation doses while still producing suboptimal images. Additionally, physical constraints, such as table weight limits and detector size, may prevent proper positioning, further compromising diagnostic accuracy. Studies indicate that radiographic sensitivity for detecting pulmonary nodules, fractures, or abdominal pathologies decreases by 15–30% in obese patients compared to those with normal body mass indices (BMIs), often necessitating alternative imaging modalities like CT or ultrasound [150-152].

Overlapping anatomical structures present another major challenge, particularly in chest, abdominal, and skeletal imaging. In standard two-dimensional radiography, superimposition of bones, organs, or foreign objects can obscure critical findings. For example, ribs overlapping lung lesions may mask early-stage tumours, while intestinal gas patterns in abdominal X-rays can mimic or conceal bowel obstructions. Similarly, in spinal imaging, the complex 3D arrangement of vertebrae makes it difficult to assess alignment, fractures, or degenerative changes without additional oblique or lateral views. While specialized projections (e.g., lordotic views for lung apices) or digital tomosynthesis can mitigate some of these limitations, they do not fully replicate the diagnostic precision of cross-sectional imaging [153, 154].

To address these challenges, modern advancements such as dual-energy subtraction, AI-assisted image enhancement, and weight-adaptive exposure algorithms are being implemented. However, fundamental physical constraints persist, reinforcing the need for judicious modality selection—particularly in obese populations or when evaluating anatomically crowded regions—to ensure diagnostic efficacy while minimizing unnecessary radiation exposure.

11. Recent Technological Advances

11.1 Digital radiography (DR) vs. traditional film.

The transition from traditional film-based radiography to digital radiography (DR) represents a significant technological evolution in medical imaging, offering substantial improvements in image quality, workflow efficiency, and dose optimization. Traditional screen-film radiography (SFR) relied on photochemical processes, where X-ray photons exposed silver halide crystals in film emulsion, requiring chemical development to produce a visible image. While SFR provided high spatial resolution (~10 lp/mm), its limitations included a narrow dynamic range, irreversible image acquisition, and inconsistent optical density due to processing variability. In contrast, DR systems utilize solid-state detectors—either indirect conversion (scintillator + photodiode arrays) or direct conversion (amorphous selenium) to transform X-ray energy directly into digital signals. This shift enables wider dynamic range, post-processing enhancement, and immediate image availability, significantly improving diagnostic versatility

DR offers several key advantages over traditional film. First, its dose efficiency reduces patient exposure by 30–50% while maintaining diagnostic quality, as digital detectors exhibit superior quantum detection efficiency (DQE) compared to film-screen combinations [155-157]. Second, advanced post-processing tools such as window-level adjustment, edge enhancement, and noise reduction allow radiologists to optimize images retrospectively without repeat exposures, a critical benefit in pediatric and trauma imaging. Third, DR eliminates film storage and chemical processing, integrating seamlessly with Picture Archiving and Communication Systems (PACS) for streamlined workflow and telemedicine applications.

However, DR is not without challenges. The initial capital cost of DR systems remains higher than film-based setups, and spatial resolution, while sufficient for most clinical applications, is theoretically lower (~3–5 lp/mm) than high-detail film. Nevertheless, the diagnostic superiority of DR in low-contrast scenarios (e.g., chest or abdominal imaging) and its integration with AI-based analytics for automated abnormality detection have cemented its dominance in modern radiology. As DR technology continues to advance, with developments like portable wireless detectors and dual-energy subtraction, it further displaces traditional film, reinforcing its role as the standard for contemporary radiographic practice [158].

11.2 AI-assisted image analysis (automated fracture detection, pneumonia screening)

The integration of artificial intelligence (AI) into radiographic image analysis represents a transformative advancement in medical imaging, particularly in automated fracture detection and pneumonia screening. AI algorithms, primarily based on deep learning convolutional neural networks (CNNs), have demonstrated remarkable accuracy in interpreting complex imaging data, augmenting diagnostic precision and workflow efficiency. In fracture detection, AI systems trained on large datasets of annotated radiographs can identify subtle cortical disruptions, trabecular fractures, and misalignments with sensitivity exceeding 90% in some studies, approaching the performance of experienced radiologists. These tools are particularly valuable in high-volume emergency departments, where they serve as "second readers" to reduce oversight of occult fractures in anatomically complex regions like the wrist, hip, or spine. Similarly, for pneumonia screening, AI models analyse chest X-rays to detect consolidations, interstitial opacities, and pleural effusions, with some algorithms achieving area-under-the-curve (AUC) values >0.95 in distinguishing bacterial from viral pneumonias—a critical distinction for guiding antibiotic therapy [159, 160].

The implementation of AI-assisted diagnostics follows two paradigms: computer-aided detection (CADe), which flags potential abnormalities for radiologist review, and computer-aided diagnosis (CADx), which provides probabilistic assessments of pathology. Both approaches leverage transfer learning from pre-trained models (e.g., ResNet, DenseNet) adapted to medical imaging. However, challenges persist, including dataset bias (underrepresentation of rare fractures or atypical pneumonias), "black box" interpretability (limited insight into AI decision pathways), and integration barriers with existing PACS workflows. Regulatory frameworks, such as the FDA's 510(k) clearance for AI radiology devices, are evolving to address these concerns while ensuring clinical safety.

Future directions include multimodal AI combining radiographs with electronic health records for context-aware analysis and edge computing for real-time processing in resource-limited settings. As these technologies mature, AI-assisted image analysis is poised to become a standard adjunct in radiology, enhancing diagnostic accuracy while mitigating interpreter fatigue and variability.

11.3 Low-dose X-ray techniques (pediatric imaging)

The development of low-dose X-ray techniques represents a critical advancement in pediatric radiology, addressing the heightened radio sensitivity of children while maintaining diagnostic efficacy. Children possess rapidly dividing cells and longer post-exposure lifespans, making them 5–10 times more vulnerable to radiation-induced stochastic effects than adults. Traditional pediatric protocols already employ weight- and age-adjusted exposure parameters, but recent innovations have further reduced doses without compromising image quality. Advanced iterative reconstruction algorithms, such as model-based iterative reconstruction (MBIR), enable 30–70% dose reduction compared to conventional filtered back projection by suppressing noise while preserving anatomical detail. Similarly, photon-counting detectors (PCDs), an emerging technology, improve dose efficiency through energy-selective imaging, eliminating electronic noise and enhancing contrast-to-noise ratios at ultra-low doses (e.g., <0.1 mSv for chest radiographs) [161, 162].

Clinical implementations include spectral shaping with copper or silver filters to remove low-energy photons that contribute to skin dose but not image formation, and adaptive collimation to minimize scattered radiation. In digital radiography (DR), artificial intelligence (AI)-based de-noising tools trained on pediatric datasets recover diagnostic information from low-exposure images, with studies demonstrating equivalent accuracy at 50% lower doses. For fluoroscopic procedures (e.g., voiding cystourethrograms), pulse-rate reduction (to 4–7.5 fps) coupled with last-image-hold functionality cuts doses by 60–80% [163, 164].

These advances align with the Image Gently® campaign guidelines, which advocate for ALARA (As Low As Reasonably Achievable) compliance in pediatric imaging. However, challenges persist in standardizing protocols across institutions and ensuring diagnostic confidence at ultra-low doses for subtle pathologies (e.g., non-displaced fractures or early pneumonia). Future directions include deep learning-based dose prediction systems that customize exposures based on individual patient anatomy and clinical indication, potentially achieving sub-micro Sievert examinations for routine screenings.

11.4 Portable and point-of-care X-ray devices (e.g., in ICUs)

The emergence of portable and point-of-care X-ray devices has revolutionized diagnostic imaging in intensive care units (ICUs), enabling bedside radiographic evaluation of critically ill patients who cannot be safely transported to fixed imaging suites. Modern portable systems incorporate lightweight, wireless flat-panel detectors and battery-powered X-ray tubes, achieving diagnostic quality comparable to stationary units while operating at lower radiation doses (typically 2–3 mGy per chest examination). These devices are particularly vital for monitoring ventilator-associated pneumonia (VAP), pneumothorax, endotracheal tube positioning, and line placements, with studies demonstrating >95% concordance between portable and fixed-unit radiographs for critical findings [165, 166].

Technological refinements have enhanced the utility of point-of-care radiography in ICUs. Motorized collimation and automatic exposure control (AEC) [167] optimize image quality while minimizing scatter radiation in crowded clinical environments. AI-powered image enhancement algorithms compensate for suboptimal positioning (common in immobile patients) by correcting rotation and magnification artifacts in real time. Some advanced portable systems now integrate dual-energy imaging, allowing bedside tissue decomposition (e.g., lung vs. bone visualization) without patient repositioning—a capability previously limited to fixed DR systems.

Infection control has driven innovation in disposable detector covers and UV-C decontamination cycles, reducing nosocomial transmission risks in immunocompromised populations. Wireless DICOM transmission via hospital networks enables immediate interpretation by off-site radiologists, expediting time-sensitive decisions. However, challenges remain in standardizing exposure protocols across diverse patient sizes and ICU settings, and in minimizing occupational exposure to staff during frequent bedside imaging. Future developments include robotic portable systems for autonomous positioning and ultra-low-field portable CT hybrids to bridge the gap between radiography and cross-sectional imaging at the point of care.

12. Future Perspectives

12.1 Integration with AI for faster, more accurate diagnoses.

The integration of artificial intelligence (AI) into radiographic imaging is poised to revolutionize diagnostic workflows by enabling faster, more accurate, and standardized interpretations. AI algorithms, particularly deep learning convolutional neural networks (CNNs), have demonstrated remarkable potential in automating image analysis, reducing interpretation times, and detecting subtle pathologies that may elude human observers. In fracture detection, for instance, AI-assisted systems have achieved sensitivity rates exceeding 95% for identifying subtle cortical disruptions and occult fractures, significantly reducing missed diagnoses in high-volume emergency settings. Similarly, in chest radiography, AI models trained on vast datasets can flag pulmonary nodules, consolidations, and pneumothoraces with accuracy comparable to experienced radiologists, while simultaneously prioritizing urgent cases for expedited review [168].

Beyond detection, AI facilitates quantitative analysis—measuring tumour growth, tracking fracture healing, or calculating cardiothoracic ratios—with precision unattainable through manual methods. Natural language processing (NLP) further enhances efficiency by automatically generating structured reports from radiologist dictations, minimizing administrative burdens. However, challenges such as algorithmic bias (due to the underrepresentation of rare conditions in training data), regulatory hurdles, and the need for human oversight persist. Future advancements will likely focus on explainable AI (XAI), which provides transparent decision-making pathways to build clinician trust, and federated learning, enabling collaborative model training across institutions without compromising patient privacy.

As AI becomes seamlessly embedded in picture archiving and communication systems (PACS), its role will expand from assistive tools to proactive diagnostic partners, offering real-time decision support and predictive analytics. Ultimately, AI integration promises to enhance diagnostic consistency, reduce radiologist burnout, and improve patient outcomes through earlier and more accurate detection of critical conditions.

12.2 Advances in photon-counting CT

Photon-counting computed tomography (PCCT) represents a transformative advancement in medical imaging, offering superior spatial and contrast resolution while simultaneously reducing radiation exposure compared to conventional energy-integrating detector (EID) CT systems. By directly converting X-ray photons into electrical signals and categorizing them by energy levels, PCCT eliminates electronic noise and enables multi-energy spectral imaging without the need for dual-source configurations. This technology achieves spatial resolutions up to 150–200 μm, allowing visualization of previously imperceptible microstructural details in coronary plaques, pulmonary nodules, and trabecular bone. Clinical studies demonstrate PCCT's ability to differentiate calcium, iodine, and uric acid with high specificity, facilitating precise tissue characterization in oncologic, vascular, and musculoskeletal applications [169].

Key innovations in PCCT include virtual non-contrast imaging, which reduces patient dose by obviating separate pre-contrast scans, and K-edge imaging, which enhances material separation for novel contrast agents. Early trials in coronary artery imaging show PCCT's potential to identify vulnerable plaques through lipid-core detection, while ultra-high-resolution lung scans improve early-stage lung cancer diagnosis. Additionally, PCCT's inherent spectral capabilities enable quantitative biomarkers for tissue perfusion and fibrosis, advancing precision medicine [170, 171].

Despite these advantages, challenges remain in scalability, cost, and workflow integration, particularly in adapting reconstruction algorithms for spectral data. Future developments aim to miniaturize detector technology for broader clinical adoption and leverage artificial intelligence for optimized image reconstruction and dose management. As PCCT evolves, it is poised to redefine diagnostic paradigms, offering unparalleled detail at lower doses, ultimately improving patient outcomes across multiple specialties.

12.3 Potential of phase-contrast and dark-field X-ray imaging

Emerging X-ray imaging techniques, particularly phase-contrast imaging (PCI) and dark-field imaging (DFI), represent a paradigm shift in medical diagnostics by exploiting previously untapped physical properties of X-ray interactions with biological tissues. Unlike conventional absorption-based radiography, which relies on differential X-ray attenuation, PCI detects phase shifts in X-ray waves as they pass through tissues, rendering visible subtle density variations in soft tissues that exhibit minimal absorption contrast. This technique enhances visualization of low-contrast structures such as tendons, ligaments, and early-stage tumours, with preclinical studies demonstrating up to 1000-fold improvement in soft-tissue contrast compared to traditional radiography. Meanwhile, DFI measures small-angle scattering from sub-pixel microstructures, providing complementary information about tissue composition at the cellular or fibrillary level—particularly valuable for assessing pulmonary microstructure, cartilage degeneration, and breast calcifications [172-174].

Current research highlights PCI's potential in neurological imaging, where it can differentiate white and gray matter without contrast agents, and in breast cancer screening, where it improves the detection of micro-calcifications and ductal abnormalities [175]. DFI, on the other hand, has shown promise in chronic lung disease diagnostics, identifying emphysema and fibrosis through characteristic scattering patterns invisible to conventional CT. Synchrotron-based studies have achieved sub-micron spatial resolution, though translation to clinical settings requires overcoming challenges in source compactness and acquisition speed.

The integration of grating-based interferometry now enables PCI and DFI with conventional X-ray tubes, paving the way for clinical adoption. Future advancements aim to combine these modalities with photon-counting detectors and AI-based reconstruction, potentially enabling multi-contrast imaging in a single scan. While technical hurdles remain in dose optimization and system portability, phase-contrast and dark-field X-ray imaging hold transformative potential for early disease detection and personalized medicine, bridging the resolution and contrast gaps between radiography and histopathology [176, 177].

12.4 Reducing radiation dose while improving image quality.

Driven by the paramount objective of reducing radiation exposure while enhancing image quality, modern radiography has leveraged technological innovations and protocol optimization. Photon-counting detectors (PCDs), for instance, significantly improve dose efficiency and enable multi-energy imaging for superior tissue differentiation. Similarly, iterative reconstruction algorithms, including those based on deep learning, preserve diagnostic fidelity at doses 50-70% lower than traditional methods. Furthermore, AI-driven exposure control systems and ultra-low-dose protocols, supported by neural network de-noising, now dynamically tailor doses to specific patient anatomy, pushing the boundaries of safe imaging. Emerging techniques like phase-contrast and dark-field imaging also offer the potential for dose-neutral soft-tissue visualization. While challenges remain in standardizing these innovations and ensuring regulatory compliance, ongoing research aims to diminish the trade-off between dose and image quality, enabling safer and more precise radiography across all patient populations [178, 179].

13. Conclusion

X-ray imaging remains a cornerstone of modern medicine due to its unique combination of speed, cost-effectiveness, and high spatial resolution for bone structures. This makes it an indispensable tool for rapid trauma assessment, fracture detection, and pulmonary screening, particularly in emergency and critical care settings. Its widespread availability and affordability also ensure equitable diagnostic access, from urban hospitals to rural clinics, securing its vital role in global health. Despite inherent limitations like ionizing radiation exposure, poor soft-tissue contrast, and 2D anatomical superimposition, significant advancements have fortified the modality. Digital radiography (DR) and sophisticated low-dose protocols have enhanced image quality and patient safety, while AI-assisted image analysis has improved diagnostic accuracy and streamlined workflows. Innovations such as portable and point-of-care X-ray systems have extended its utility to intensive care and remote environments. Future developments promise to further overcome these challenges. Technologies like photon-counting detectors and phase-contrast imaging are expected to provide superior tissue characterization and mitigate traditional soft-tissue limitations. The growing integration of artificial intelligence will enable more automated diagnostics and personalized dose optimization. As research continues to refine these techniques and address persistent issues like dose management and 3D visualization constraints, X-ray imaging will further solidify its role as a foundational tool, bridging its historical reliability with cutting-edge innovation to support precision diagnostics and personalized healthcare.

14. References

[1] S. Arati, Panchbhai “Wilhelm Conrad Röntgen and the discovery of X-rays: Revisited after centennial,” vol. 27,1, pp. 90-95, 2015.

[2] R. R. Babic, G. S. Babic, S. R. Babic., “120 Years Since the discovery of X-Rays/120. Godina od otkrica X-Zraka,” vol. 69,9-10, pp. 323-331, 2016.

[3] PM Dunn, and n. edition, “Wilhelm Conrad Röentgen (1845–1923), the discovery ofx rays and perinatal diagnosis,” vol. 84,2, pp. F138-F139, 2001.

[4] F. J. P. M. Nüsslin, “Wilhelm Conrad Röntgen: The scientist and his discovery,” vol. 79, pp. 65-68, 2020.

[5] RF Mould, and Biology, “The early history of x-ray diagnosis with emphasis on the contributions of physics 1895-1915,” Phys Med Biol vol. 40,11, pp. 1741, 1995.

[6] UF Rosenow, “Notes on the legacy of the Röntgen rays,” vol. 22,11, pp. 1855-1867, 1995.

[7] A. Stewart, W. Pennybacker, and R. J. B. M. J. Barber, “Adult leukaemias and diagnostic x rays,” Br Med J vol. 2,5309, pp. 882, 1962.

[8] M. Godfrey Hochbaum, “Why people seek diagnostic x-rays,” Public Health Rep (1896) vol. 71,4, pp. 377, 1956.

[9]G.M Ardran, Mathematical, and P. Sciences, “The application and limitation of the use of X-rays in medical diagnosis,” Philos Trans R Soc, vol. 292,1390, pp. 147-156, 1979.

[10] E. T. Parks, and G. F. J. J. C. D. P. Williamson, “Digital radiography: an overview,” J Contemp Dent Pract vol. 3,4, pp. 23-39, 2002.

[11] J. J. V. Mattoon, C. Orthopaedics, and Traumatology, “Digital radiography,” Vet Comp Orthop Traumatol vol. 19,03, pp. 123-132, 2006.

[12] M. Korner, C. H. Weber, S. Wirth et al., “Advances in digital radiography: physical principles and system overview,” Radiographics vol. 27,3, pp. 675-686, 2007.

[13] F. Paul, van der Stelt, “Better imaging: the advantages of digital radiography,” J Am Dent Assoc vol. 139, pp. S7-S13, 2008.

[14] T. M. Buzug, "Computed tomography," Springer handbook of medical technology, pp. 311-342: Springer, 2011.

[15] M. Mazonakis, and J. J. E. j. o. r. Damilakis, “Computed tomography: What and how does it measure?” vol. 85,8, pp. 1499-1504, 2016.

[16] Sharon L. Brooks, “Computed tomography,” Dent Clin North Am vol. 37,4, pp. 575-590, 1993.

[17] P. Shrimpton, M. Hillier, M. Lewis et al., Doses from computed tomography (CT) examinations in the UK-2003 review: NRPB Chilton, 2005.

[18] M. J. R. Mahesh, “Fluoroscopy: patient radiation exposure issues,” Radiographics vol. 21,4, pp. 1033-1045, 2001.

[19] D. Miller, “Overview of contemporary interventional fluoroscopy procedures,” Health Phys vol. 95,5, pp. 638-644, 2008.

[20] B. Daly, and P. A. J. R. Templeton, “Real-time CT fluoroscopy: evolution of an interventional tool,” Radiology vol. 211,2, pp. 309-315, 1999.

[21] E. Ron, “Cancer risks from medical radiation,” Health Phys vol. 85,1, pp. 47-59, 2003.

[22] M. S. Linet, T. L. Slovis, D. L. Miller et al., “Cancer risks associated with external radiation from diagnostic imaging procedures,” CA Cancer J Clin vol. 62,2, pp. 75-100, 2012.

[23] D. J. Brenner, and E. J. J. T. l. Hall, “Risk of cancer from diagnostic X-rays,” Lancet vol. 363,9427, pp. 2192, 2004.

[24] E. Karavas, B. Ece, S. Aydın et al., “Are we aware of radiation: A study about necessity of diagnostic X-ray exposure,” vol. 12,4, pp. 264, 2022.

[25] S. O. Hansson, “Improvement principles,” J Safety Res vol. 69, pp. 33-41, 2019.

[26] S. O. Hansson, "Zero visions and other safety principles," The Vision Zero Handbook: Theory, Technology and Management for a Zero Casualty Policy, pp. 1-75: Springer, 2022.

[27] P. A. Bryant, “Radiation Protection Optimisation in New Nuclear Build: Challenges in the application of the As Low As Reasonably Achievable (ALARA) Principle,” University of Surrey, 2021.

[28] N. F. A. Nor Azman, S. A. Othman, N. F. Abu Bakar et al., “Safety culture in handling radioactive materials: a review,” 2018.

[29] A. Clement David-Olawade, D. B. Olawade, L. Vanderbloemen et al., “AI-Driven Advances in Low-Dose Imaging and Enhancement—A Review,” vol. 15,6, pp. 689, 2025.

[30] I.-S. Tzeng, P.-C. Hsieh, W.-L. Su et al., “Artificial Intelligence-assisted chest X-ray for the diagnosis of COVID-19: A systematic review and meta-analysis,” Diagnostics (Basel), vol. 13,4, pp. 584, 2023.

[31] R. V. Gupta, M. K. Kalra, S. Ebrahimian et al., “Complex relationship between artificial intelligence and CT radiation dose,” Academic Radiology vol. 29,11, pp. 1709-1719, 2022.

[32] S. Schumann, B. Thelen, S. Ballestra et al., “X-ray image calibration and its application to clinical orthopedics,” Med Eng Phys vol. 36,7, pp. 968-974, 2014.

[33] K. Mori, N. Sekine, H. Sato et al., “Application of synchrotron X-ray imaging to phase objects in orthopedics,” J Synchrotron Radiat vol. 9,3, pp. 143-147, 2002.

[34] A. M. Davies, and H. Pettersson, Orthopedic imaging: techniques and applications: Springer Science & Business Media, 2012.

[35] M. K. Santos, J. Elias Júnior, F. M. Mauad et al., “Magnetic resonance imaging of the chest: current and new applications, with an emphasis on pulmonology,” J Bras Pneumol vol. 37,2, pp. 242-258, 2011.

[36] I. N. Wijma, R. F. Casal, G. Z. Cheng et al., “Radiation Principles, Protection, and Reporting for Interventional Pulmonology: A World Association of Bronchology and Interventional Pulmonology White Paper,” Respiration vol. 103,11, pp. 707-721, 2024.

[37] R. Vliegenthart, A. Fouras, C. Jacobs et al., “Innovations in thoracic imaging: CT, radiomics, AI and x-ray velocimetry,” Respirology vol. 27,10, pp. 818-833, 2022.

[38] S. Oprea, C. Marinescu, I. Lita et al., "Image processing techniques used for dental x-ray image analysis." pp. 125-129.

[39] A. Kumar, H. S. Bhadauria, and A. J. P. C. S. Singh, “Descriptive analysis of dental X-ray images using various practical methods: A review,” Peerj Computer Science vol. 7, pp. e620, 2021.

[40] M. Uo, T. Wada, and T. J. J. D. S. R. Sugiyama, “Applications of X-ray fluorescence analysis (XRF) to dental and medical specimens,” Japanese Dental Science Review vol. 51,1, pp. 2-9, 2015.

[41] L. Yang, L.-g. Ye, J.-b. Ding et al., “Use of a full-body digital X-ray imaging system in acute medical emergencies: a systematic review,” Emerg Med J vol. 33,2, pp. 144-151, 2016.

[42] E. Fatihoglu, S. Aydin, F. D. Gokharman et al., “X-ray use in chest imaging in emergency department on the basis of cost and effectiveness,” Acad Radiol vol. 23,10, pp. 1239-1245, 2016.

[43] R. Khan, S. Siddique, F. Jabeen et al., “Role of chest X-ray and Lung Ultrasound in diagnosis and treatment of Children and Infants with Pneumonia,” vol. 27,4, pp. 352-363, 2021.

[44] M. Elsharkawy, A. Sharafeldeen, F. Taher et al., “Early assessment of lung function in coronavirus patients using invariant markers from chest X-rays images,” Sci Rep vol. 11,1, pp. 12095, 2021.

[45] W. Y. N. Naing, Z. Z. J. S. Htike, and I. Processing, “Advances in automatic tuberculosis detection in chest x-ray images,” vol. 5,6, pp. 41, 2014.

[46] S. A Patil, and Citeseer “Texture analysis of TB X-ray images using image processing techniques,” vol. 3,1, pp. 53-56, 2012.

[47] E. L. Irede, O. R. Aworinde, O. K. Lekan et al., “Medical imaging: a critical review on X-ray imaging for the detection of infection,” pp. 1-45, 2024.

[48] B. Jany, and T. Welte, “Pleural effusion in adults—etiology, diagnosis, and treatment,” vol. 116,21, pp. 377, 2019.

[49] J. E. Heffner, J. S. Klein, and C. J. C. Hampson, “Diagnostic utility and clinical application of imaging for pleural space infections,” Chest vol. 137,2, pp. 467-479, 2010.

[50] J. M. Porcel, M. Azzopardi, C. Koegelenberg et al., “The diagnosis of pleural effusions,” Expert Rev Respir Med vol. 9,6, pp. 801-815, 2015.

[51] D. Pfeiffer, F. Pfeiffer, and E. J. M. I. i. O. Rummeny, “Advanced X-ray imaging technology,” Recent Results Cancer Res vol. 216, pp. 3-30, 2020.

[52] J. A. Seibert, “Projection x-ray imaging: Radiography, mammography, fluoroscopy,” Health Phys vol. 116,2, pp. 148-156, 2019.

[53] P. C. Johns, and M. J. J. M. p. Yaffe, “Theoretical optimization of dual-energy x-ray imaging with application to mammography,” Med Phys vol. 12,3, pp. 289-296, 1985.

[54] A. Karellas, and S. J. M. p. Vedantham, “Breast cancer imaging: a perspective for the next decade,” Med Phys vol. 35,11, pp. 4878-4897, 2008.

[55] Z. S. Lima, M. R. Ebadi, G. Amjad et al., “Application of imaging technologies in breast cancer detection: a review article,” Open Access Maced J Med Sci vol. 7,5, pp. 838, 2019.

[56] S. Di Maria, S. Vedantham, and P. J. E. J. o. R. Vaz, “X-ray dosimetry in breast cancer screening: 2D and 3D mammography,” Eur J Radiol vol. 151, pp. 110278, 2022.

[57] A. C. Lardo, “Real-time magnetic resonance imaging: diagnostic and interventional applications,” Pediatr Cardiol vol. 21,1, pp. 80-98, 2000.

[58] M. Diana, P. Halvax, B. Dallemagne et al., “Real-time navigation by fluorescence-based enhanced reality for precise estimation of future anastomotic site in digestive surgery,” Surg Endosc vol. 28,11, pp. 3108-3118, 2014.

[59] G. Katti, S. A. Ara, and A. J. I. j. o. d. c. Shireen, “Magnetic resonance imaging (MRI)–A review,” vol. 3,1, pp. 65-70, 2011.

[60] T. Dill, “Contraindications to magnetic resonance imaging,” Heart vol. 94,7, pp. 943-948, 2008.

[61] P. N. T. Wells, and biology, “Ultrasound imaging,” Phys Med Biol vol. 51,13, pp. R83, 2006.

[62] M. A. Schellpfeffer, “Ultrasound imaging in research and clinical medicine,” Birth Defects Res C Embryo Today vol. 99,2, pp. 83-92, 2013.

[63] N. Pace, L. Ricci, and S. J. S. Negrini, “A comparison approach to explain risks related to X-ray imaging for scoliosis, 2012 SOSORT award winner,” Scoliosis vol. 8,1, pp. 1-7, 2013.

[64] D. F. Regulla, and H. J. R. p. d. Eder, “Patient exposure in medical X-ray imaging in Europe,” Radiat Prot Dosimetry vol. 114,1-3, pp. 11-25, 2005.

[65] U. Arndt, “Generation of X-rays,” 2006.

[66] H. Hayashi, N. Kimoto, T. Asahara et al., “Photon counting detectors for x-ray imaging,” vol. 10, pp. 978-973, 2021.

[67] H. A. Kramers, Edinburgh, D. P. Magazine, and J. o. Science, “XCIII. On the theory of X-ray absorption and of the continuous X-ray spectrum,” vol. 46,275, pp. 836-871, 1923.

[68] P. Gorenstein, H. Gursky, and G. J. A. J. Garmire, vol. 153, p. 885, “The analysis of X-ray spectra,” vol. 153, pp. 885, 1968.

[69] J. A. Seibert, “X-ray imaging physics for nuclear medicine technologists. Part 1: Basic principles of x-ray production,” J Nucl Med Technol vol. 32,3, pp. 139-147, 2004.

[70] P. Russo, “2.01 Physical basis of X-ray imaging,” pp. 1-48, 2014.

[71] S. Kulpe, M. Dierolf, B. Günther et al., “Spectroscopic imaging at compact inverse Compton X-ray sources,” Physica Medica-European Journal of Medical Physics vol. 79, pp. 137-144, 2020.

[72] G. Harding, B. J. R. p. Schreiber, and chemistry, “Coherent X-ray scatter imaging and its applications in biomedical science and industry,” Radiation Physics and Chemistry vol. 56,1-2, pp. 229-245, 1999.

[73] T. J. Petrone, Energy optimization and scatter in chest radiography: Rutgers The State University of New Jersey, School of Graduate Studies, 1995.

[74] P. E. Kinahan, B. H. Hasegawa, and T. Beyer, "X-ray-based attenuation correction for positron emission tomography/computed tomography scanners." pp. 166-179.

[75] K. LaCroix, B. Tsui, B. Hasegawa et al., “Investigation of the use of X-ray CT images for attenuation compensation in SPECT,” Ieee Transactions on Nuclear Science vol. 41,6, pp. 2793-2799, 1994.

[76] N. Kotwaliwale, P. R. Weckler, and G. H. J. B. e. Brusewitz, “X-ray attenuation coefficients using polychromatic X-ray imaging of pecan components,” Biosystems Engineering vol. 94,2, pp. 199-206, 2006.

[77] G. L. Locher, “The compound photoelectric effect of X-rays in light elements,” Physical Review vol. 40,4, pp. 484, 1932.

[78] H. Hall, “The theory of photoelectric absorption for x-rays and γ-rays,” vol. 8,4, pp. 358, 1936.

[79] C.-K. Qiao, J.-W. Wei, and L. J. C. Chen, “An overview of the compton scattering calculation,” Crystals vol. 11,5, pp. 525, 2021.

[80] R. Pratt, L. LaJohn, V. Florescu et al., “Compton scattering revisited,” Radiation Physics and Chemistry vol. 79,2, pp. 124-131, 2010.

[81] M. Cooper, P. Mijnarends, N. Shiotani et al., X-ray Compton scattering: OUP Oxford, 2004.

[82] F. Aharonian, A. J. A. Atoyan, and S. Science, “Compton scattering of relativistic electrons in compact X-ray sources,” Astrophysics and Space Science vol. 79,2, pp. 321-336, 1981.

[83] F. Van der Veen, and F. J. J. o. P. C. M. Pfeiffer, “Coherent x-ray scattering,” vol. 16,28, pp. 5003, 2004.

[84] B. J. N. Lengeler, “Coherence in X-ray physics,” Naturwissenschaften vol. 88,6, pp. 249-260, 2001.

[85] D. Joshi, and T. P. J. A. I. R. Singh, “A survey of fracture detection techniques in bone X-ray images,” Artificial Intelligence Review vol. 53,6, pp. 4475-4517, 2020.

[86] F. Hardalaç, F. Uysal, O. Peker et al., “Fracture detection in wrist X-ray images using deep learning-based object detection models,” vol. 22,3, pp. 1285, 2022.

[87]P Simoni, “Optimisation of X-Rays Imaging Techniques for the Assessment of Joint Space,” J Belg Soc Radiol vol. 102,1, pp. 23, 2018.

[88] C. Spampinato, S. Palazzo, D. Giordano et al., “Deep learning for automated skeletal bone age assessment in X-ray images,” Med Image Anal vol. 36, pp. 41-51, 2017.

[89] V. De Sanctis, S. Di Maio, A. T. Soliman et al., “Hand X-ray in pediatric endocrinology: Skeletal age assessment and beyond,” Indian J Endocrinol Metab vol. 18, Suppl 1, pp. S63-S71, 2014.

[90] A. Horng, E. Brun, A. Mittone et al., “Cartilage and soft tissue imaging using X-rays: propagation-based phase-contrast computed tomography of the human knee in comparison with clinical imaging techniques and histology,” Invest Radiol vol. 49,9, pp. 627-634, 2014.

[91] S.A. Jebb, “Measurement of soft tissue composition by dual energy X-ray absorptiometry,” Br J Nutr vol. 77,2, pp. 151-163, 1997.

[92] W.R Hendee “History and status of x-ray mammography,” Health Phys vol. 69,5, pp. 636-648, 1995.

[93] V. Rebuffel, J.-M. J. I.-n.-d. t. Dinten, and c. monitoring, “Dual-energy X-ray imaging: benefits and limits,” Insight vol. 49,10, pp. 589-594, 2007.

[94] H. MacMahon, F. Li, R. Engelmann et al., “Dual energy subtraction and temporal subtraction chest radiography,” J Thorac Imaging vol. 23,2, pp. 77-85, 2008.

[95] H. Chen, M. M. Rogalski, and J. N. J. P. C. C. P. Anker, “Advances in functional X-ray imaging techniques and contrast agents,” Phys Chem Chem Phys vol. 14,39, pp. 13469-13486, 2012.

[96] X. Li, N. Anton, G. Zuber et al., “Contrast agents for preclinical targeted X-ray imaging,” Adv Drug Deliv Rev vol. 76, pp. 116-133, 2014.

[97] S. Kositbowornchai, R. Nuansakul, S. Sikram et al.,

"Root fracture detection: a comparison of direct digital radiography with conventional radiography," Dentomaxillofac Radiol vol. 30,2, pp. 106-109, 2001.

[98] L. Yin, A. Basu, and J. K. J. P. R. Chang, "Scalable edge enhancement with automatic optimization for digital radiographic images," Pattern Recognition vol. 37,7, pp. 1407-1422, 2004.

[99] W. Chen, X. Liu, K. Li et al., "A deep-learning model for identifying fresh vertebral compression fractures on digital radiography," Eur Radiol vol. 32,3, pp. 1-10, 2022.

[100] S. Jett, M. K. Shrout, J. M. Mailhot et al., "An evaluation of the origin of trabecular bone patterns using visual and digital image analysis," Oral Surg Oral Med Oral Pathol Oral Radiol Endod vol. 98,5, pp. 598-604, 2004.

[101] A. Meesters, K. Ten Duis, J. Kraeima et al., "The accuracy of gap and step-off measurements in acetabular fracture treatment," Sci Rep vol. 11,1, pp. 18294, 2021.

[102]ML Sampaio, and Reporting, "Fracture Healing and Complications of Fractures," pp. 341-377, 2012.

[103] A. Niiya, K. Murakami, R. Kobayashi et al., "Development of an artificial intelligence-assisted computed tomography diagnosis technology for rib fracture and evaluation of its clinical usefulness," Sci Rep vol. 12,1, pp. 8363, 2022.

[104] M. Miniati, S. Monti, J. Stolk et al., "Value of chest radiography in phenotyping chronic obstructive pulmonary disease," Eur Respir J vol. 31,3, pp. 509-515, 2008.

[105] D. Wootton, and C. J. P. Feldman, "The diagnosis of pneumonia requires a chest radiograph (x-ray)—yes, no or sometimes?," vol. 5,1, pp. 1-7, 2014.

[106] G. E. Hayden, and K. W. J. T. J. o. e. m. Wrenn, "Chest radiograph vs. computed tomography scan in the evaluation for pneumonia," J Emerg Med vol. 36,3, pp. 266-270, 2009.

[107] R. Piccazzo, F. Paparo, and G. J. T. J. o. R. S. Garlaschi, "Diagnostic accuracy of chest radiography for the diagnosis of tuberculosis (TB) and its role in the detection of latent TB infection: a systematic review," J Rheumatol Suppl vol. 91, pp. 32-40, 2014.

[108] M. M. Oken, W. G. Hocking, P. A. Kvale et al., "Screening by chest radiograph and lung cancer mortality: the Prostate, Lung, Colorectal, and Ovarian (PLCO) randomized trial," JAMA vol. 306,17, pp. 1865-1873, 2011.

[109] M. M. Oken, P. M. Marcus, P. Hu et al., "Baseline chest radiograph for lung cancer detection in the randomized Prostate, Lung, Colorectal and Ovarian Cancer Screening Trial," J Natl Cancer Inst vol. 97,24, pp. 1832-1839, 2005.

[110] J. Kim, and K. H. J. T. l. c. r. Kim, "Role of chest radiographs in early lung cancer detection," Transl Lung Cancer Res vol. 9,3, pp. 522, 2020.

[111] J. Gohagan, P. Marcus, R. Fagerstrom et al., "Baseline findings of a randomized feasibility trial of lung cancer screening with spiral CT scan vs chest radiograph: the Lung Screening Study of the National Cancer Institute," Chest vol. 126,1, pp. 114-121, 2004.

[112] Z. Nxumalo, E. Irusen, B. Allwood et al., "The utility of artificial intelligence in identifying radiological evidence of lung cancer and pulmonary tuberculosis in a high-burden tuberculosis setting," S Afr Med J vol. 114,6, pp. 29-31, 2024.

[113] J.C. Wandtke, "Bedside chest radiography," Radiology vol. 190,1, pp. 1-10, 1994.

[114] L. Delrue, R. Gosselin, B. Ilsen et al., "Difficulties in the interpretation of chest radiography," pp. 27-49, 2011.

[115] Z. Szucs-Farkas, A. Schick, J. L. Cullmann et al., "Comparison of dual-energy subtraction and electronic bone suppression combined with computer-aided detection on chest radiographs: effect on human observers' performance in nodule detection," AJR Am J Roentgenol vol. 200,5, pp. 1006-1013, 2013.

[116] J. D. Balkman, S. Mehandru, E. DuPont et al., "Dual energy subtraction digital radiography improves performance of a next generation computer-aided detection program," J Thorac Imaging vol. 25,1, pp. 41-47, 2010.

[117] J. Iannucci, and L. J. Howerton, Dental radiography-E-book: principles and techniques: Elsevier Health Sciences, 2016.

[118] C. W. Douglass, R. W. Valachovic, A. Wijesinha et al., "Clinical efficacy of dental radiography in the detection of dental caries and periodontal diseases," Oral Surg Oral Med Oral Pathol vol. 62,3, pp. 330-339, 1986.

[119] B. E. Angmar-Månsson, S. Al-Khateeb, and S. J. J. o. d. e. Tranæus, "Caries diagnosis," J Dent Educ vol. 62,10, pp. 771-780, 1998.

[120] E. Levander, R. Bajka, and O. J. T. E. J. o. O. Malmgren, "Early radiographic diagnosis of apical root resorption during orthodontic treatment: a study of maxillary incisors," Eur J Orthod vol. 20,1, pp. 57-63, 1998.

[121] H. Crow, E. Parks, J. Campbell et al., "The utility of panoramic radiography in temporomandibular joint assessment," Dentomaxillofac Radiol vol. 34,2, pp. 91-95, 2005.

[122] R. H. Sukhia, R. Nuruddin, S. I. Azam et al., "Predicting the sagittal skeletal pattern using dental cast and facial profile photographs in children aged 9 to 14 years," J

Pak Med Assoc vol. 72,11, pp. 2198-2203, 2022.

[123] R. D. Leathers, and R. E. J. A. O. M. S. C. N. A. Gowans, “Office-based management of dental alveolar trauma,” Atlas Oral Maxillofac Surg Clin North Am vol. 21,2, pp. 185-197, 2013.

[124] J. De Mey, B. O. De Beeck, M. Meysman et al., “Real time CT-fluoroscopy: diagnostic and therapeutic applications,” Eur J Radiol vol. 34,1, pp. 32-40, 2000.

[125] K. Katada, R. Kato, H. Anno et al., “Guidance with real-time CT fluoroscopy: early clinical experience,” Radiology vol. 200,3, pp. 851-856, 1996.

[126] E. Seeram, E. J. D. R. P. P. Seeram, and Q. Control, “Digital fluoroscopy,” pp. 95-110, 2019.

[127] D.J. DiSantis, “Gastrointestinal fluoroscopy: what are we still doing?” vol. 191,5, pp. 1480-1482, 2008.

[128] S. J. Leibovic, and W. J. J. T. B. J. o. R. Caldicott, “Gastrointestinal fluoroscopy: patient dose and methods for its reduction,” Br J Radiol vol. 56,670, pp. 715-719, 1983.

[129] M. S. Levine, P. Ramchandani, and S. E. Rubesin, Practical Fluoroscopy of the GI and GU Tracts: Cambridge University Press, 2012.

[130] V.A Duddalwar, “Multislice CT angiography: a practical guide to CT angiography in vascular imaging and intervention,” Br J Radiol vol. 77, suppl_1, pp. S27-S38, 2004.

[131] R. A. Byrne, S. Cassese, M. Linhardt et al., “Vascular access and closure in coronary angiography and percutaneous intervention,” Nat Rev Cardiol vol. 10,1, pp. 27-40, 2013.

[132] D. Bernardi, P. Macaskill, M. Pellegrini et al., “Breast cancer screening with tomosynthesis (3D mammography) with acquired or synthetic 2D mammography compared with 2D mammography alone (STORM-2): a population-based prospective study,” Lancet Oncol vol. 17,8, pp. 1105-1113, 2016.

[133] M. Elzaki, “Evidence on synthesized two-dimensional mammography versus digital mammography when using tomosynthesis (three-dimensional mammography) for population breast cancer screening,” Clinical Breast Cancer vol. 18,4, pp. 255-260. e251, 2018.

[134] J. M. Lewin, C. J. D'Orsi, R. E. Hendrick et al., “Clinical comparison of full-field digital mammography and screen-film mammography for detection of breast cancer,” AJR Am J Roentgenol vol. 179,3, pp. 671-677, 2002.

[135] S. Batchu, F. Liu, A. Amireh et al., “A review of applications of machine learning in mammography and future challenges,” Oncology vol. 99,8, pp. 483-490, 2021.

[136] M. A. Baysal, and E. Toker, "CMOS cassette for digital upgrade of film-based mammography systems." pp. 615-623.

[137] Y.-H. Hu, M. Masiar, and W. Zhao, "Breast structural noise in digital breast tomosynthesis and its dependence on reconstruction methods." pp. 598-605.

[138] H. R. Peppard, B. E. Nicholson, C. M. Rochman et al., “Digital breast tomosynthesis in the diagnostic setting: indications and clinical applications,” Radiographics vol. 35,4, pp. 975-990, 2015.

[139] H. Wobser, R. Wiest, B. Salzberger et al., “Evaluation of treatment response after chemoembolisation (TACE) in hepatocellular carcinoma using real time image fusion of contrast-enhanced ultrasound (CEUS) and computed tomography (CT)-preliminary results,” Clin Hemorheol Microcirc vol. 57,2, pp. 191-201, 2014.

[140] Y. Yu, M. Guo, X. J. C. b. Han et al., “Comparison of multi-slice computed tomographic angiography and dual-source computed tomographic angiography in resectability evaluation of pancreatic carcinoma,” Cell Biochem Biophys vol. 70,2, pp. 1351-1356, 2014.

[141] K. Nieman, M. Oudkerk, B. J. Rensing et al., “Coronary angiography with multi-slice computed tomography,” Lancet vol. 357,9256, pp. 599-603, 2001.

[142] T. Flohr, B. J. M.-s. Ohnesorge, and D.-s. C. i. C. Imaging, “Multi-slice CT technology,” pp. 41-69, 2007.

[143] M. F. Reiser, C. R. Becker, K. Nikolaou et al., Multislice ct: Springer Science & Business Media, 2008.

[144] B. M. Ohnesorge, Multi-Slice CT in Cardiac Imaging: Technical Principles, Clinical Applications and Future Developments: Springer Science & Business Media, 2002.

[145] A. Inamdar, and R. K. J. C. Shinde, “The diagnostic impact of contrast-enhanced computed tomography (CECT) in evaluating lymph node involvement in colorectal cancer: a comprehensive review,” Cureus vol. 16,6, pp. e61832, 2024.

[146] J. Huang, W. Chen, and S. J. M. Yao, “Assessing diagnostic value of contrast-enhanced ultrasound and contrast-enhanced computed tomography in detecting small hepatocellular carcinoma: A meta-analysis,” Medicine (Baltimore), vol. 96,30, pp. e7555, 2017.

[147] X. Ou, X. Chen, X. Xu et al., “Recent development in x-ray imaging technology: Future and challenges,” Research (Wash D C) vol. 2021, pp. 9892152, 2021.

[148] H. A. Field Jr, "Uses and Limitations of X-Ray Pictures as Evidence." p. 219.

[149] E. L. J. A. i. X.-r. a. Ritman, “Medical x-ray imaging, current status and some future challenges,” vol. 49, pp. 1-

12, 2006.

[150] M. J. Müller, W. Braun, J. Enderle et al., “Beyond BMI: conceptual issues related to overweight and obese patients,” vol. 9,3, pp. 193-205, 2016.

[151] M. J. Modica, K. M. Kanal, and M. L. J. R. Gunn, “The obese emergency patient: imaging challenges and solutions,” Radiographics vol. 31,3, pp. 811-823, 2011.

[152] M. S. Lopes, P. P. Freitas, M. C. Carvalho et al., “Challenges for obesity management in a unified health system: the view of health professionals,” Fam Pract vol. 38,1, pp. 4-10, 2021.

[153] L. T. Niklason, B. T. Christian, L. E. Niklason et al., “Digital tomosynthesis in breast imaging,” Radiology vol. 205,2, pp. 399-406, 1997.

[154] J. T. Dobbins III, H. P. McAdams, D. J. Godfrey et al., “Digital tomosynthesis of the chest,” vol. 23,2, pp. 86-92, 2008.

[155] P. C. Bunch, K. E. Huff, and R. J. J. o. t. O. S. o. A. A. Van Metter, “Analysis of the detective quantum efficiency of a radiographic screen–film combination,” vol. 4,5, pp. 902-909, 1987.

[156] R. M. Nishikawa, and M. J. J. M. p. Yaffe, “Effect of various noise sources on the detective quantum efficiency of phosphor screens,” Medical Physics vol. 17,5, pp. 887-893, 1990.

[157] P. C. Bunch, "Detective quantum efficiency of selected mammographic screen-film combinations." pp. 67-77.

[158] W.T. Drost, “Transitioning to digital radiography,” J Vet Emerg Crit Care (San Antonio), vol. 21,2, pp. 137-143, 2011.

[159] M. Cellina, M. Cè, G. Irmici et al., “Artificial intelligence in emergency radiology: where are we going?” Diagnostics (Basel), vol. 12,12, pp. 3223, 2022.

[160] A. Kalyanpur, and N. J. A. M. Mathur, “Applications of artificial intelligence in thoracic imaging: a review,” vol. 2,1, 2025.

[161] G. Kalifa, Y. Charpak, C. Maccia et al., “Evaluation of a new low-dose digital x-ray device: first dosimetric and clinical results in children,” Pediatr Radiol vol. 28,7, pp. 557-561, 1998.

[162] T. Hugh, Morgan, “Dose reduction for CT pediatric imaging,” Pediatr Radiol vol. 32,10, pp. 724-728; discussion 751-724, 2002.

[163] E. H. Silver, S. D. Shulman, and M. M. J. M. P. Rehani, “Innovative monochromatic x-ray source for high-quality and low-dose medical imaging,” Med Phys vol. 48,3, pp. 1064-1078, 2021.

[164] J. Wong, P. Kutschera, and K. K. J. J. o. c. a. t. Lau, “Spectral Shaping Computed Tomography Applications,” pp. 10.1097, 2022.

[165] S. Rajsic, R. Breitkopf, M. Bachler et al., “Diagnostic modalities in critical care: point-of-care approach,” Diagnostics (Basel), vol. 11,12, pp. 2202, 2021.

[166 M. Di Serafino, G. Dell’Aversano Orabona, M. Caruso et al., “Point-of-Care Lung Ultrasound in the Intensive Care Unit—The Dark Side of Radiology: Where Do We Stand?,” vol. 13,11, pp. 1541, 2023.

[167] D. Gutierrez, S. Schmidt, A. Denys et al., “CT-automatic exposure control devices: What are their performances?”, vol. 580,2, pp. 990-995, 2007.

[168] Y. E. Almalki, A. Qayyum, M. Irfan et al., "A novel method for COVID-19 diagnosis using artificial intelligence in chest X-ray images." p. 522.

[169] S. S. Hsieh, S. Leng, K. Rajendran et al., “Photon counting CT: clinical applications and future developments,” IEEE Trans Radiat Plasma Med Sci vol. 5,4, pp. 441-452, 2020.

[170] A. Meloni, F. Frijia, D. Panetta et al., “Photon-counting computed tomography (PCCT): technical background and cardio-vascular applications,” Diagnostics (Basel), vol. 13,4, pp. 645, 2023.

[171] A. C. Alves, A. Ferreira, G. Luijten et al., “Deep PCCT: Photon Counting Computed Tomography Deep Learning Applications Review,” 2024.

[172] M. C. Zdora, “State of the Art of X-ray Speckle-Based Phase-Contrast and Dark-Field Imaging,” Journal of Imaging vol. 4,5, pp. 60, 2018.

[173] F. Pfeiffer, M. Bech, O. Bunk et al., “X-ray dark-field and phase-contrast imaging using a grating interferometer,” Journal of Applied Physics vol. 105,10, 2009.

[174] T. Thüring, R. Guggenberger, H. Alkadhi et al., “Human hand radiography using X-ray differential phase contrast combined with dark-field imaging,” vol. 42,6, pp. 827-835, 2013.

[175] S. J. Hoffman, A. H. Yee, J. P. Slusser et al., “Neuroimaging patterns of ischemic stroke after percutaneous coronary intervention,” Catheter Cardiovasc Interv vol. 85,6, pp. 1033-1040, 2015.

[176] M.-C. J. J. o. I. Zdora, “State of the art of X-ray speckle-based phase-contrast and dark-field imaging,” Journal of Imaging vol. 4,5, pp. 60, 2018.

[177] T. Thüring, R. Guggenberger, H. Alkadhi et al., Human hand radiography using X-ray differential phase contrast combined with dark-field imaging, 0364-2348, Springer, 2013.

[178] S. L. Brady, A. T. Trout, E. Somasundaram et al., “Improving image quality and reducing radiation dose for pediatric CT by using deep learning reconstruction,” Radiology vol. 298,1, pp. 180-188, 2021.

[179] C. Catalano, M. Francone, A. Ascarelli et al., “Optimizing radiation dose and image quality,” Eur Radiol vol. 17, Suppl 6, pp. 26-32, 2007.