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Advancing X-Ray Medical Imaging through Compton Scattering Technologies: A Systematic Review of Technological Developments and AI-Based Image Reconstruction

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ABSTRACT

Compton scattering has emerged as a promising advancement in X-ray medical imaging, offering enhanced spatial resolution and diagnostic precision compared to conventional techniques. This study employs a Systematic Literature Review (SLR) to evaluate the contributions of Compton scattering technologies in improving imaging performance. Forty peer-reviewed articles were selected from six major databases including Google Scholar, Scopus, PubMed, Web of Science, ScienceDirect, and arXiv based on predefined inclusion criteria. The review identifies three main technological approaches which are Compton cameras, inverse Compton X-ray sources, and Compton scattering tomography. Recent innovations in image reconstruction, particularly using deep learning and convolutional neural networks, have significantly improved image quality, reduced noise, and enhanced computational efficiency. These findings underscore Compton scattering's clinical potential, especially in soft tissue visualization and early lesion detection. This paper provides a detailed overview of current progress and strategic pathways in the development of Compton based imaging systems towards their clinical application.

Keywords: compton scattering, x-ray imaging, compton tomography, inverse compton source, image reconstruction, machine learning, medical diagnostics

INTRODUCTION

X-ray imaging has long been of paramount importance in clinical diagnostics, mainly due to its capability to noninvasively probe internal anatomy. It is commonly used for pathology of the oncologic, cardiovascular, and musculoskeletal system [1]. However, traditional X-ray radiography has limitations on the contrast sensitivity or the spatial resolution [2]. These limitations may contribute to a delay in the early diagnosis and limit its accuracy, particularly in doubtful or borderline individuals. To overcome these limitations, the technological developments in the field have been geared more towards achieving better image quality and aiding diagnosis.

Compton scattering is one of the most attractive physical concepts in the field of present-day medical-imaging technology [3]. This is the quasielastic scattering of the incoming X-ray photon on a bound electron and its redistribution to another bound electron: since the two atoms oscillate around a central point, the two bound electrons are shaking aside/opposite of them and the pertinent processes have a maximum for impact parallel and antiparallel to the interatomic axis. The scattering angle and energy shift of the scattered photons contain structural information and provide compositional information that is not present in classic absorption based imaging methods of the mammogram [4-6]. This mechanism of interaction enables the imaging modality of Compton scattering to provide better spatial resolution and contrast, particularly for soft tissue imaging [7-8].

Based on this physical principle, a number of system architectures have emerged in order to harness this Compton scattering for clinical and research use. These are Compton cameras, inverse Compton sources and Compton scattering tomography (CST). More generally, Compton cameras are well-established in improving soft tissue contrast and localization of radioactive sources, especially in nuclear medicine [7, 9]. In contrast, UIC sources can generate compact high-energy X-ray beams with the possibility of tuning the spectra, which provide better portability and scalability [10-12]. In the case of CST systems, the volumetric imaging can be realized based on the scattered photon at wide angles, so 3D reconstruction without physical rotation of the device can be expected [13-16].

Compton scattering technology, however, has not gained wide acceptance in the clinic [17-18]. despite the great potential of this technique. Technological problems, such as complex data processing, heavy noise contamination, and less-accurate image reconstruction, still impose limitations on the performance of real-time imaging [19-20]. Other barriers are related to hardware limitations, high operation cost and the requirement of special knowledge for interpretation of results from these systems [21-22].

In compliance with PRISMA guidelines, we carry out a systematic review of forty articles, representing peer-reviewed research, published in the period 2004-2025, in order to evaluate recent advances in the Compton scattering based technology for X-ray medical imaging. The review aims at pinpointing such technological advances, presenting an overview on the development history of image reconstruction techniques with focus on the integration of artificial intelligence, summarizing diagnostic performance (strengths and limitations) of the methods and providing the reader with a guidance on what potential strengths and drawbacks to expect when integrating Compton-based device or scanners into the clinic [23-25].

METHODS

The paper is based on the systematic literature review (SLR) that aims at investigating the use of Compton scattering in the field of medical imaging. The review is conducted following the PRISMA 2020 guidelines which contribute to transparency, reproducibility and completeness in the selection and analysis of articles [14]. A combined number of 1,785 items were identified in six scientific databases: Google Scholar (n = 726), Scopus (n = 360), ScienceDirect (n = 226), PubMed (n = 189), arXiv (n = 161), and Web of Science (n = 123).

The search strategy used Boolean operators with the following terms: (“Compton scattering” OR “Compton camera” OR “inverse Compton” OR “Compton tomography”) AND (“medical imaging” OR “X-ray diagnostics” OR “image reconstruction”). The use of Boolean logic ensured broad coverage while maintaining focus on the topic.

After removing 520 duplicates, 1,265 articles proceeded to the title and abstract screening stage. From these, 1,049 records were excluded due to irrelevance, poor methodological quality, or incomplete information. The remaining 216 full-text articles were evaluated against predefined inclusion and exclusion criteria. TABLE 1 summarizes these criteria, which guided the eligibility assessment.

TABLE 1. Inclusion and Exclusion Criteria for Article Selection

Criteria	Inclusion	Exclusion
Document Type	Peer-reviewed and indexed journal articles	Non-reviewed proceedings, blogs, opinion pieces
Publication Year	2004–2025	Outside this range
Language	English	Languages other than English
Topic Focus	Compton scattering in medical imaging	Topics unrelated to imaging (e.g., security, geophysics, etc.)
Content Focus	Compton cameras, inverse Compton, CST, image reconstruction, AI-based imaging	Articles not directly discussing imaging systems
Accessibility	Full-text available and accessible	Articles with restricted or incomplete access

This review followed the PRISMA 2020 guidelines to ensure transparency in article selection. The literature search was conducted across six scientific databases: Google Scholar (n = 726), Scopus (n = 360), ScienceDirect (n = 226), PubMed (n = 189), arXiv (n = 161), and Web of Science (n = 123). The search used a Boolean operator combination: (“Compton scattering” OR “Compton camera” OR “inverse Compton” OR “Compton tomography”) AND (“medical imaging" OR "X-ray diagnostics" OR "image reconstruction"). This formulation was intended to maximize coverage while maintaining relevance to the research scope.

After removing 520 duplicate records, 1,265 articles proceeded to the screening phase. A total of 1,049 were excluded based on irrelevance, poor methodological quality, or lack of access to full-text content. The remaining 216 full-text articles were assessed in detail, resulting in 176 exclusions due to insufficient data, lack of alignment with technological focus, or deviation from the study scope.

To enhance comprehensiveness, backward snowballing was also performed by reviewing reference lists from the included articles. As a result, 37 studies were selected for qualitative synthesis. These were thematically categorized into three research domains: (1) technological innovations such as Compton cameras, inverse Compton sources, and Compton scattering tomography (CST) [26-27]; (2) image reconstruction methods, particularly those involving artificial intelligence [28]; and (3) clinical implementation challenges and future development opportunities [29]. The article selection process is summarized in FIGURE 1.

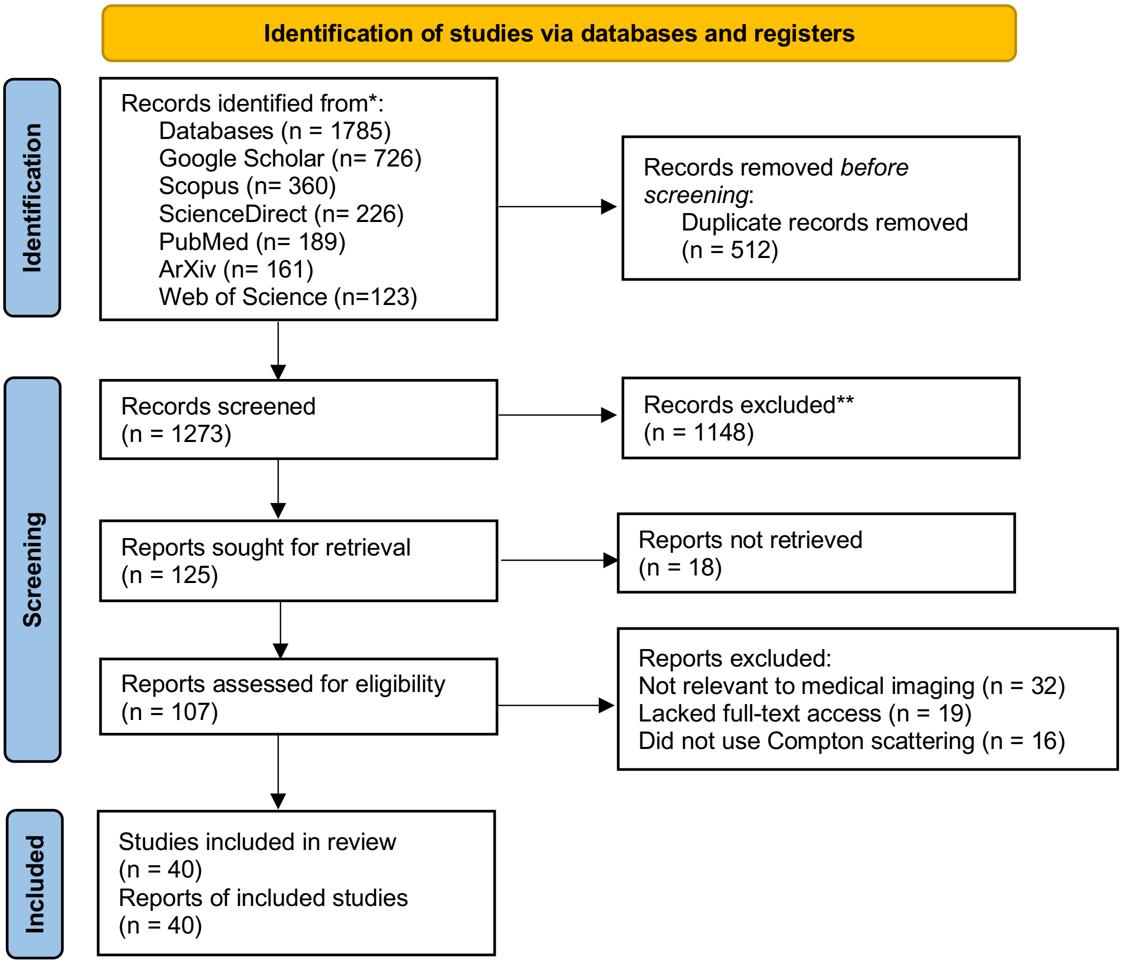

FIGURE 1. PRISMA flow diagram illustrating the study selection process for articles on Compton scattering in medical imaging

RESULTS AND DISCUSSIONS

Technological Advances in Compton Imaging Systems

Research on Compton scattering in medical imaging has shown significant growth over the past two decades. Based on the 37 articles reviewed in this study, the majority of publications emerged between 2015 and 2025. This fact shows that Compton scattering has become an important research topic in exploring the new imaging technique with the X-ray sources with high brightness [8]. A notable increase in publications since 2020 aligns with growing demand for advanced imaging diagnostics during the pandemic and progress in compact X-ray source technologies. A trend on this shift of emphasis from system development to clinical applications and integration with artificial intelligence [12, 23] was also observed among the main articles published after 2020.

Regarding institutions, the greatest number of papers are produced by institutions where there are well-developed medical technology research centers in some countries (US, Japan, Germany, and S. Korea). Research institutions such as Lawrence Berkeley National Laboratory and KEK Japan, in addition to medical research institution located in Eastern European countries contributed considerably to the advancement of Compton cameras and tomography-systems based on imaging [9]. Recent trends also indicate that more research efforts are appearing in multidisciplinary publications, which is symptomatic for the convergence between physics, biomedical engineering and computer sciences. This means that the use of Compton scatter is no longer restricted to medical physics but is now a feature of more general healthcare technology developments [19].

FIGURE 2 shows the disciplinary breadth of the journals that have published research on Compton scattering in medical imaging, demonstrating the interdisciplinary nature of the field. As the figure shows, the Journal fields represented in the 37 articles selected are depicted in chart 1. The dataset is dominated by medical physics and radiology, accounting for around 40% of all publications. This is indicative of the general clinical orientation of Compton scattering research and its application directly to diagnostic imaging.

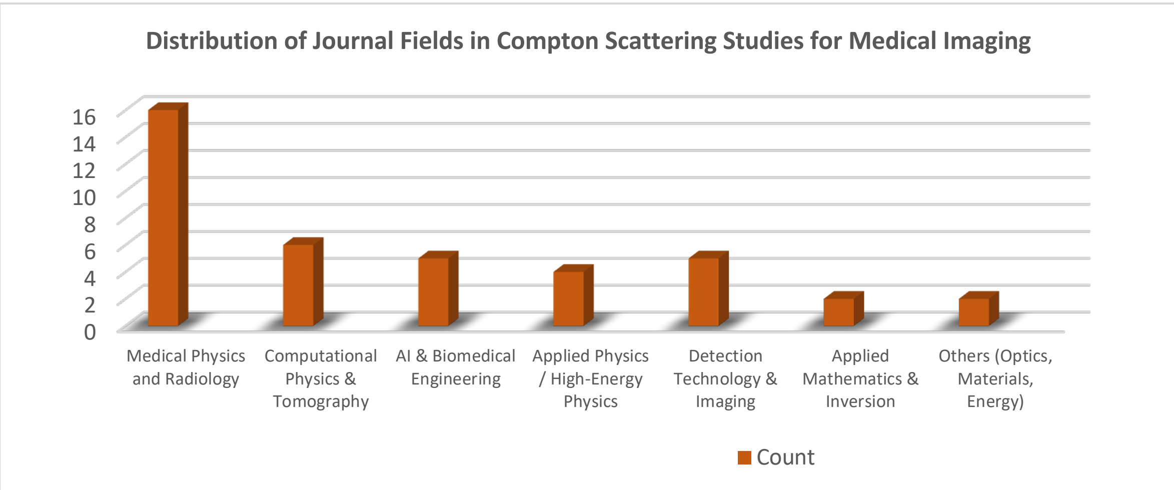

FIGURE 2. Distribution of Research Areas in Articles on Compton Scattering in Medical Imaging (2004–2025)

Some papers are also covered in areas such as computational physics and tomography, which are vital in signal processing and image reconstruction techniques [19-20]. Publications in the field of artificial intelligence and biomedical engineering demonstrate the integration of intelligent systems in image enhancement and object recognition [8]. Further contributions to the field come from applied and high-energy physics, detection technology and development of imaging systems that focus on the technological basis of Compton-based instrumentation [10-11]. Fewer, but from applied mathematics, inversion methods and material and optical sciences indicate a rising inter-disciplinary interest. In summary, the distribution shows that Compton scattering study in medical imaging is across fields. It is a representative example of the confluence of physics, engineering, and computer-aided methods to address changing clinical requirements.

Technical advances in Compton scatter imaging in medicine focuses on three primary methods. The first one is the Compton cameras as dual scattering-based detection systems. This system is designed to improve image resolution and detection angle versatility [7, 9]. Such cameras are frequently utilized in radiotracer imaging and isotope-based radiotherapy [30-31]. The second method is by means of inverse Compton scattering (ICS) sources. Such sources produce X-rays of high energy and narrow spectrum, being the result of the interaction of electron beams with lasers [2, 10]. It is believed that this system is more compact and low cost comparing to conventional sources (tubes and synchrotrons) [11, 32]. The third category is constituted by Compton Scattering Tomography (CST) systems. This allows for 3D data generation in wide-angle scattering and it's detection from several positions [20, 33]. CST reconstructs internal distribution without rotating object, and it is applicable to the real time. There are pros and cons for each. Compton cameras are much more flexible, but have lower resolution for large volumes. ICS sources provide better X-ray quality, albeit with complex setups. CST offers 3D spatial reconstruction but it requires extremely accurate algorithms and detectors [8, 34].

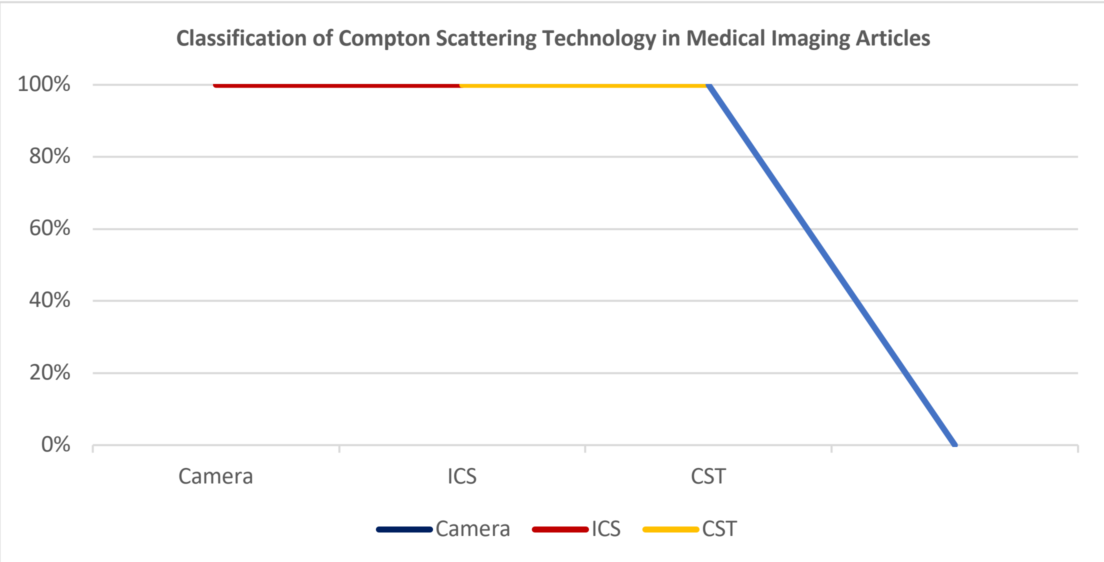

FIGURE 3. Classification of Compton Scattering Technology in Medical Imaging Articles

A classification of the major technological sectors in the reviewed articles (Compton cameras, inverse Compton sources and Compton scattering tomography) is shown in FIGURE 3. As shown in the figure, three major classes consist of Compton cameras, inverse Compton X-ray sources and Compton Scattering Tomography (CST) systems. Each class refers to a one differential method to produce, receive and reconstruct diagnostic image. This figure shows the distribution of articles that correspond to each approach according to the systematic literature review performed in the present study.

After the system-level developments discussed in the previous section, the following addresses the actual image reconstruction processes. This section describes how algorithmic progress, especially those leveraging artificial intelligence, has led to advances in image quality, diagnostic accuracy and computational gain in Compton Imaging systems.

Image Reconstruction Techniques and Quality Assessment

Reconstruction is the key technique in Compton scattering based imaging systems. It is a procedure for retrieving spatial details of a test object from photon scatter data, based on the energy and the scattering angle measurements of the detection system [8, 19]. The theoretical foundation of reconstruction based on Compton scattering is rooted in the wavelength relationship before and after scattering. The photon scattering angle can be determined using the Compton equation, where $\Delta\lambda$ is the difference in wavelength and λ is the wavelength:

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - cos\theta)\,. \tag{1}$$

The formula shows that the change in wavelength ($\lambda'-\lambda$) depends on the scattering angle (θ). This parameter is a key factor in the determination of the position of the photon source in 3D space [3, 5].

In the initial phase of system development, classical image reconstruction algorithms, like FBP, were adopted. However, this method is ineffective to cope with the angular and energy distribution complexity. Currently, however, most methods are based on Maximum Likelihood Expectation Maximization (MLEM) algorithm because it can take into account uncertainties in the scatter data [28, 35]. Recent developments include the use of AI in image reconstruction. Methods that rely on CNN and Deep Learning have been introduced to enhance accuracy and achieve fast computation [23, 36]. Hybrid MLEM and CNN models are also included in some studies, generating higher-resolution spatial reconstructions [8].

A comparison of three basic methods for image reconstruction in Compton scattering system was shown in TABLE 2. The FBP algorithm is a traditional reconstruction technique, which is rapid and simple, but it does not perform well in spatial resolution, contrast, and noise reduction aspects [19]. The MLEM method significantly improves the spatial accuracy, but it has longer computing costs and more complicated iterative procedures [20]. On the other hand, AI-based (CNN) methods are able to generate sharp and relatively less noisy image in comparatively less time. The modeling complexity in AIbased reconstruction is high, but it is justified by the imaging quality enhancement [8, 23].

TABLE 2. Comparison of Image Reconstruction Methods in Compton Scattering Systems

Reconstruction Method	Spatial Accuracy	Noise Reduction	Computation Time	Algorithm Complexity
FBP (Filtered Back Projection)	Low-Moderate	Low	Fast	Low
MLEM (Maximum Likelihood Expectation Maximization)	High	Moderate-High	Slow	High
CNN / AI-based	Very High	High	Very Fast	Very High

The image quality is an important index to measure the performance of Compton scattering image devices. A number of parameters are important for medical diagnostics and these include spatial resolution, tissue contrast, signal-to-noise ratio (SNR) and anatomical accuracy [17-18]. A few studies demonstrate that scatter-based approaches can provide better contrast of soft tissue than found with standard X-ray imaging. This is predominantly because the scattering method has the capability to image the distribution of electron density in tissues in more detail [1, 9]. The quality of images is also enhanced with the optimization of detection systems and development of reconstruction methods. Systems with high-resolution detectors and MLEM or CNN methods present images with low noise and with a sharper boundary of the imaged object [8]. In addition, recent studies suggest that summing inverse Compton sources can greatly increase the SNR ratio [10-11]. In several studies they demonstrated that the ability of the Compton camera to detect small lesions (lung nodules, tumor tissues) has been proved. The findings indicate that the diagnostic sensitivity is high, particularly if combined with aperture code systems or hybrid imaging [30-31].

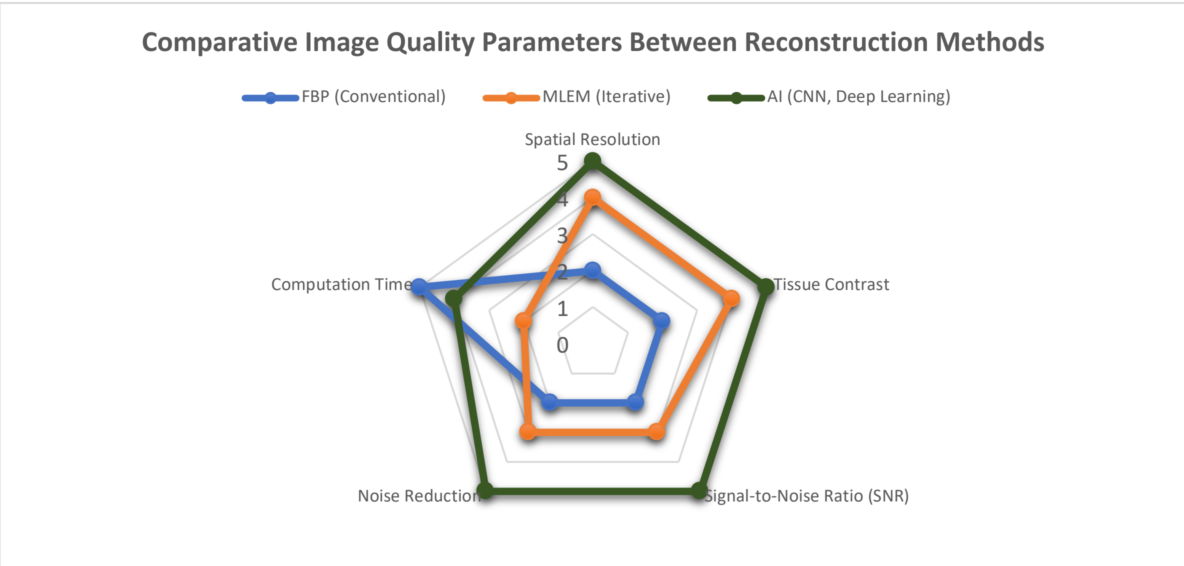

FIGURE 4. Comparative Image Quality Parameters Between Reconstruction Methods. Scale Description: 1 = very poor, 2 = low, 3 = moderate, 4 = high, 5 = very high.

FIGURE 4 shows a radar plot between 3 main image reconstruction softwares: FBP, MLEM, and AI (i.e., using CNN & Deep learning). It is evaluated by five key image quality parameters: spatial resolution, tissue contrast, SNR (signal to noise ratio), noise reduction, and computational time. Of the three methods, AI reconstruction yields the best performance in all parameters. It achieves the best performance in three aspects including spatial resolution, tissue contrast and SNR and favorable performance in noise suppression as well as fast computation. This is an indication to the effectiveness of deep learning algorithms to improve image quality and diagnostic accuracy.

As an iterative method, MLEM strikes a good balance. It has better spatial resolution and acceptable noise reduction than FBP, however at the expense of much longer processing times. While MLEM is computationally more costly, it can be used in scenarios of interest, which can benefit from further image detail. In contrast, FBP is the worst for most of the measures. Although fast in reconstruction, its less noise reduction and poorer contrast have confined its diagnostic use in the super resolution imaging.

In summary, the chart shows a clear movement toward the AI winning in image reconstruction, with the implications for enhanced diagnostic quality of images achieved in the most computationally efficient way. These results further suggest that future Compton-based imaging systems will require more and more on AI-guided reconstruction to achieve the required speed and accuracy for clinical applications. The MLEM performs with enhanced spatial resolution and contrast as compared with FBP, but its computational cost is much higher. On the other hand, AI-based reconstruction is superior in many of the aspects, particularly that of generating high resolution and high contrast by efficient noise suppression, which could be even faster compared to recent hardware optimized ones.

Our results suggest that AI reconstruction has greatly enhanced image quality and reconstruction speed over traditional methods such as FBP or MLEM. The computational efficiency and image quality have been greatly improved based on the reconstruction methods, but technical and clinical challenges remain as well. These challenges are examined in more detail in the next section and we consider there implications for real-world medical adoption.

Challenges and Future Directions

The development of Compton scattering systems for medical imaging is still limited due to several technological issues. One of the dominant problems is the excessive noise due to the amount of scatter double or random scatter is irrelevant. This noise degrades contrast in images as well as makes the tissue segmentation challenging [17, 19]. This model is also very sensitive to the geometric arrangement between the source, the object and the detector. Fine variations in angle or distance give rise to transposition in reconstructed images [33-34]. Reconstruction accuracy is highly sensitive to calibration errors and detector resolution [20, 37].

Computational time is also a barrier. Algorithms such as MLEM are iterative and require long processing times, especially when applied to three-dimensional data volumes. This limits their application for real-time imaging in clinical settings [26]. System size and operational costs also pose barriers to clinical adoption. Laser-based radiation sources or inverse Compton systems require specialized infrastructure that is not yet available in general healthcare facilities [10-11]. On the other hand, Compton camera hardware still faces limitations in wide-angle data acquisition and simultaneous multi-energy detection [9].

TABLE 3. Main Challenges and Proposed Solutions in Compton Scattering Systems

Technical Challenges	Impact on the System	Potential Solutions
High noise from multiple scattering	Decreased image quality	Statistical filtering, AI-based processing
Complex system geometry	Inaccurate reconstruction	Precision calibration, adaptive 3D systems
Long computation time	Unsuitable for real-time applications	AI-based reconstruction (CNN, GPU acceleration)
High cost and large system size	Difficult adoption in general hospitals	Source miniaturization, portable detectors
Limited detector resolution	Inability to detect small lesions	High-energy and multi-layer sensors

TABLE 3 summarizes key technical challenges encountered in Compton-based systems, such as high noise from multiple scatter events and long processing times. Several studies suggest AI-based reconstruction and adaptive 3D geometry as potential solutions [31-32]. Research on Compton scattering in medical imaging is now shifting towards the integration of smart technology and compact systems. One of the main innovations is the application of artificial intelligence (AI) algorithms to accelerate and refine the image reconstruction process. CNN in combination with deep learning is applied to eliminate noise and sharpen tissue boundaries [8].

Recently, focus has been placed on the development of systems for real-time imaging. Researchers have begun to deploy GPU acceleration and edge computing processing in order to carry out direct spatial reconstruction at the point of examination [23]. This is in an effort to improve clinical throughput and the timeliness of diagnostic results [19]. Another advancement is the demonstration of compact inverse Compton sources. These sources are orders of magnitude smaller than synchrotrons, yet they can produce high-energy X-rays with narrow spectra 8. Therefore, these devices can be employed as the components of portable imaging systems for emergency room and operation room.

Furthermore, trend of the research is oriented to the multi-imaging, Compton imaging coupled with other modalities, i.e. the PET, CT, or MRI. The objective is to improve physiological and anatomical contrast in the same system [30-31]. The systematic review, which includes 37 articles, indicates that Compton scattering has a high impact in the improvement of the quality of X-ray imaging for medical purposes. This provides high spatial resolution, excellent tissue contrast and the possibility of internal structure detection [17-18].

Compton camera systems appear to be well suited to extend the imaging coverage, particularly for small lesions and soft tissues. The inverse Compton radiation sources in conjunction serve as a more efficient and compact radiation source alternative [10-11]. There are also developments in AI-based reconstruction that demonstrate significant advances in the speed and quality of image processing [8]. Nevertheless, several issues need to be resolved, including high system complexity, requirements for accurate calibration, and high implementation cost [35]. In this work, we have summarized the previous work by classifying the technologies according to system approaches, considering the image quality for every technology, and developing solutions for those problems.

The contribution of this work is mainly on the innovative trend of Compton scattering development. In addition, this research offers suggestions for portable systems, the integration of AI and the future of hybrid imaging. The results can provide a literature-based reference for the development and application of this technique in clinical practice.

CONCLUSION

37 peer-reviewed articles were reviewed for the current systematic literature review to assess the contribution of Compton scattering towards advancing X-ray medical imaging. The results emphasize three primary technology paths: Compton cameras, inverse Compton sources, and Compton scattering tomography (CST), each providing unique diagnostic and system level performance enhancements. DICOM: artificial intelligenceET) Deep learning has played a major role in image reconstruction, resulting in for better spatial resolution, faster computation, and significant noise suppression. The review reports well identified synergies in technology integration, including real-time reconstruction, multimodal hybrid systems, and miniaturized hardware for clinical environment. These developments have direct impacts for low-invasive diagnostics and high-resolution imaging procedures.

While substantial progress has been achieved, there are still challenging barriers, such as signal noise introduced by multi-scatter, algorithm standardization and high system complexity, which have impeded wider clinical applications. This article provides a rigorous overview of the current research domain and highlights the imperative to validate these initiatives through collaborative partnerships among institutions. It is anticipated that future studies will integrate large-scale controlled research, cost-effectiveness investigations and systems study and government policy research to help more Comptonbased technologies make the transition from experimental systems for medical imaging to those used routinely.

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