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Photon-Counting Computed Tomography in the Era of Precision Medicine: Technological Advances, Artificial Intelligence Integration, and Multidisciplinary Clinical Applications

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ABSTRACT

Photon-Counting Computed Tomography (PCCT) has emerged as one of the most significant innovations in diagnostic imaging by introducing photon-counting detector technology capable of overcoming several intrinsic limitations of conventional energy-integrating detector computed tomography. This review analyzes the technological principles underlying PCCT, its integration with artificial intelligence, current clinical applications, implementation challenges, and future perspectives in precision medicine. A structured review of the contemporary scientific literature was conducted using internationally recognized biomedical databases and peer-reviewed

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publications focusing on detector technology, spectral imaging, quantitative imaging biomarkers, radiation dose optimization, and multidisciplinary clinical applications. The reviewed evidence consistently demonstrated that PCCT provides superior spatial resolution, improved contrast-to-noise ratio, enhanced spectral imaging, quantitative tissue characterization, and substantial reduction of electronic noise and beam-hardening artifacts while maintaining lower radiation exposure than conventional CT systems. The greatest clinical benefits were observed in cardiovascular imaging, oncology, neurology, pediatric radiology, pulmonary imaging, abdominal imaging, and musculoskeletal applications. The integration of artificial intelligence further enhances image reconstruction, automated segmentation, lesion detection, radiomics, workflow optimization, and quantitative image analysis, facilitating increasingly individualized diagnostic assessment. Despite important challenges related to acquisition costs, infrastructure requirements, protocol standardization, and broader clinical implementation, the available evidence supports Photon-Counting Computed Tomography as a transformative technology with the potential to redefine diagnostic imaging and strengthen the development of precision medicine across diverse healthcare systems.

KEYWORDS

Photon-Counting Computed Tomography, Photon-Counting CT, Computed Tomography, Artificial Intelligence, Spectral Imaging, Diagnostic Imaging, Radiomics, Precision Medicine, Cardiovascular Imaging, Oncology, Neurology, Radiation Dose, Medical Imaging, Quantitative Imaging.

INTRODUCTION

Computed tomography (CT) has become one of the most transformative diagnostic imaging modalities in modern medicine, fundamentally changing the evaluation of acute and chronic diseases across virtually every medical specialty. Since its clinical introduction in the early 1970s, continuous technological innovations—including multidetector CT, iterative reconstruction algorithms, dual-energy CT, and artificial intelligence (AI)-assisted image analysis—have substantially improved image quality, acquisition speed, and diagnostic confidence while progressively reducing radiation exposure [7], [16]. Despite these remarkable advances, conventional energy-integrating detector computed tomography (EID-CT) remains constrained by inherent physical limitations related to detector architecture, electronic noise, limited spatial resolution, beam-hardening artifacts, and reduced spectral discrimination. These technical constraints can compromise lesion characterization, tissue differentiation, visualization of small anatomical structures, and quantitative imaging, particularly in complex cardiovascular, neurological, oncological, and multisystem diseases [8], [11], [16].

The emergence of Photon-Counting Computed Tomography (PCCT) represents one of the most significant technological breakthroughs in diagnostic imaging since the introduction of multidetector CT. Unlike conventional systems, photon-counting detectors directly convert incoming X-ray photons into electrical signals while simultaneously recording the energy of each individual photon. This fundamental technological shift enables true spectral imaging without increasing radiation dose, significantly improves spatial resolution, reduces electronic noise, minimizes beam-hardening artifacts, and provides superior contrast resolution compared with traditional detector technologies [8], [13], [16]. These characteristics position PCCT as a transformative platform capable of expanding both anatomical and functional imaging while supporting quantitative imaging biomarkers that may substantially improve diagnostic accuracy and individualized patient care.

The transition from energy-integrating detectors to photon-counting technology reflects decades of advances in detector physics, semiconductor engineering, computational image reconstruction, and medical imaging informatics. Early experimental investigations demonstrated the theoretical superiority of direct photon-counting systems for maximizing signal-to-noise ratio and enhancing material discrimination through energy-resolved photon detection [13], [14]. However, significant engineering challenges—including pulse pile-up, charge sharing, detector dead time, semiconductor stability, and high-speed signal processing—initially limited clinical implementation. Continuous improvements in cadmium telluride (CdTe) and cadmium zinc telluride (CZT) detector materials, combined with

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sophisticated electronic architectures and reconstruction algorithms, have enabled the successful translation of photon-counting technology from research laboratories into commercially available clinical scanners [8], [14].

Recent years have witnessed rapid expansion in the clinical adoption of PCCT, accompanied by an increasing body of evidence demonstrating its potential across multiple medical disciplines. Cardiovascular imaging has emerged as one of the earliest areas benefiting from this technology, where improved visualization of coronary arteries, enhanced plaque characterization, reduction of blooming artifacts caused by calcifications, and superior assessment of coronary stents have significantly increased diagnostic confidence [3], [10], [15]. The capability to acquire ultra-high-resolution images while maintaining lower radiation doses is particularly valuable for patients requiring serial cardiovascular evaluations and those with heavily calcified coronary vessels, circumstances in which conventional CT often exhibits important diagnostic limitations [15], [16].

In oncological imaging, photon-counting CT offers unprecedented opportunities for tumor characterization through improved tissue contrast, enhanced iodine quantification, spectral material decomposition, and quantitative radiomic feature extraction. These capabilities facilitate more accurate lesion detection, tumor staging, treatment monitoring, and evaluation of therapeutic response, supporting the growing paradigm of precision oncology [3], [6], [18]. Furthermore, the improved spectral performance allows more accurate differentiation between viable tumor tissue, fibrosis, necrosis, and treatment-induced changes, potentially reducing diagnostic uncertainty in patients undergoing chemotherapy, immunotherapy, or targeted molecular therapies [4], [18].

Neurological imaging also stands to benefit considerably from photon-counting technology. High spatial resolution enables improved visualization of intracranial vessels, cerebral microcalcifications, subtle ischemic changes, and small hemorrhagic lesions that may remain inconspicuous on conventional CT examinations. Enhanced spectral imaging further facilitates differentiation among various intracranial pathologies while reducing beam-hardening artifacts in the posterior fossa and skull base, areas that have historically presented significant diagnostic challenges [1], [3], [10]. As cerebrovascular diseases continue to represent one of the leading causes of mortality and long-term disability worldwide, improvements in early imaging diagnosis may have substantial implications for patient outcomes and healthcare systems.

Beyond individual organ systems, PCCT has demonstrated promising applications in abdominal imaging, musculoskeletal disorders, pulmonary diseases, vascular medicine, and pediatric radiology. Improved visualization of interstitial lung abnormalities, enhanced detection of pulmonary embolism, superior characterization of renal and hepatic lesions, better evaluation of bone microarchitecture, and reduced metal artifacts around orthopedic implants illustrate the versatility of this emerging technology [3], [6], [18]. In pediatric imaging, where minimizing radiation exposure remains a critical priority, the combination of lower radiation doses with higher image quality may substantially improve diagnostic safety while preserving diagnostic performance [3].

An equally important development accompanying photon-counting CT is its close integration with artificial intelligence. Modern AI techniques—including deep learning reconstruction, convolutional neural networks, radiomics, machine learning classifiers, and automated segmentation algorithms—are increasingly being incorporated into imaging workflows to optimize image reconstruction, reduce noise, enhance lesion detection, automate quantitative measurements, and support clinical decision-making [5], [12]. Rather than functioning as isolated innovations, AI and photon-counting CT represent complementary technologies whose combined implementation may redefine diagnostic imaging by enabling faster image acquisition, improved diagnostic reproducibility, personalized risk stratification, and automated extraction of imaging biomarkers that extend beyond human visual interpretation [5].

The integration of spectral imaging with artificial intelligence further supports the emergence of quantitative imaging as a cornerstone of precision medicine. Instead of relying exclusively on qualitative image interpretation, clinicians may increasingly utilize objective imaging biomarkers that quantify tissue composition, vascularity, calcification burden, iodine concentration, and microstructural changes. Such biomarkers have the potential to improve disease phenotyping, predict therapeutic response, facilitate longitudinal monitoring, and support individualized treatment strategies across numerous clinical scenarios [4], [5], [17]. Consequently, PCCT may contribute not only to earlier diagnosis but also to more accurate prognostic assessment and personalized clinical management.

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Despite these considerable technological advantages, important challenges remain before photon-counting CT achieves widespread implementation. The high acquisition costs of novel scanners, infrastructure requirements, limited global availability, need for specialized radiologist training, standardization of quantitative biomarkers, regulatory considerations, interoperability with existing imaging systems, and the necessity for large multicenter validation studies continue to represent significant barriers to universal adoption [3], [6], [19]. Furthermore, while initial clinical studies consistently demonstrate superior technical performance compared with conventional CT, long-term evidence regarding cost-effectiveness, clinical outcomes, workflow optimization, and healthcare system integration remains under active investigation [1], [4].

These implementation challenges are particularly relevant for low- and middle-income regions, including many countries in Latin America, where disparities in access to advanced imaging technologies continue to influence healthcare delivery. Nevertheless, increasing international collaborations, expanding academic research networks, technological cost reductions, and broader dissemination of AI-assisted imaging platforms may progressively facilitate the incorporation of photon-counting CT into tertiary referral centers across Latin America. Participation of institutions from Brazil, Mexico, Argentina, Chile, Colombia, and other regional healthcare systems in multicenter imaging research will likely play an important role in validating the technology under diverse clinical and socioeconomic conditions while promoting equitable access to next-generation diagnostic imaging.

Given the rapid evolution of this field, continuous synthesis of the available scientific evidence has become increasingly necessary. Numerous reviews have addressed isolated aspects of photon-counting CT, including detector physics, cardiovascular applications, oncological imaging, or technical performance [1]–[6], [8], [10]. However, comprehensive analyses integrating the technological foundations, artificial intelligence applications, multispecialty clinical implementation, quantitative imaging capabilities, and future perspectives remain comparatively limited, particularly from an international perspective that also considers the opportunities and challenges facing healthcare systems in Latin America.

Accordingly, the present review aims to provide a comprehensive and updated analysis of photon-counting computed tomography by examining its physical principles, technological evolution, detector architecture, integration with artificial intelligence, current clinical applications across multiple medical specialties, implementation challenges, and future directions in precision medicine. The review is based on a critical synthesis of contemporary scientific literature retrieved from internationally recognized biomedical databases and peer-reviewed publications, emphasizing recent evidence that reflects the current state of clinical implementation. Through this integrative approach, the article seeks to provide physicians, radiologists, researchers, and healthcare professionals with a comprehensive understanding of the transformative potential of photon-counting CT as one of the most important innovations shaping the future of diagnostic imaging.

DEVELOPMENT

Photon-counting computed tomography (PCCT) represents a paradigm shift in diagnostic imaging because it fundamentally changes the way X-ray photons are detected and processed. Unlike conventional energy-integrating detector CT (EID-CT), which measures the total energy deposited by incoming photons, PCCT counts each individual photon and simultaneously records its energy level. This direct conversion process substantially improves image quality while enabling spectral information to be obtained from a single acquisition, thereby overcoming several intrinsic limitations of conventional CT systems [8], [13], [16].

From a technological perspective, the superiority of PCCT originates from its detector architecture. Conventional detectors employ scintillator materials that convert X-ray photons into visible light before producing electrical signals, a process that inevitably introduces signal loss and electronic noise. In contrast, photon-counting detectors use semiconductor materials such as cadmium telluride (CdTe) or cadmium zinc telluride (CZT), allowing direct conversion of X-ray photons into electrical impulses with minimal information loss [13], [14]. Consequently, detector efficiency increases, electronic noise is substantially reduced, and spatial resolution improves without requiring higher radiation exposure.

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One of the most important advances introduced by PCCT is spectral imaging through energy discrimination. Every detected photon is classified according to its energy, enabling simultaneous acquisition of multiple energy datasets from a single scan. This capability allows precise differentiation of tissues based on their attenuation characteristics, facilitating material decomposition and quantitative imaging that were previously achievable only through dedicated dual-energy CT protocols [7], [17]. As a result, iodine maps, virtual non-contrast images, calcium characterization, and multi-material decomposition become more accurate and clinically applicable.

Improved spatial resolution constitutes another defining characteristic of photon-counting CT. Detector elements are considerably smaller than those used in conventional scanners, permitting visualization of anatomical structures at submillimeter resolution. This increased detail is particularly valuable in cardiovascular imaging, where accurate assessment of coronary arteries, small vascular branches, and coronary stents remains technically challenging using conventional CT because of blooming artifacts caused by calcified plaques [3], [10], [15]. Clinical studies have demonstrated that PCCT significantly reduces these artifacts, improving visualization of vessel lumen and enhancing diagnostic confidence during coronary artery evaluation.

Similarly, neurological imaging benefits from the higher spatial and spectral resolution offered by PCCT. The technology enables improved visualization of cerebral microvasculature, subtle intracranial hemorrhage, early ischemic lesions, and skull base anatomy while reducing beam-hardening artifacts that frequently compromise image interpretation in conventional CT examinations [1], [3]. These improvements are particularly relevant in emergency medicine, where rapid and accurate diagnosis directly influences therapeutic decisions and neurological outcomes.

Oncological imaging has become one of the most promising fields for clinical implementation of photon-counting CT. Enhanced tissue contrast and quantitative iodine imaging improve lesion detection, tumor characterization, and treatment monitoring across multiple malignancies. Furthermore, improved spectral information facilitates differentiation between viable tumor tissue, fibrosis, necrosis, and post-treatment changes, reducing diagnostic uncertainty during patient follow-up [4], [18]. These capabilities align closely with the principles of precision oncology, where individualized therapeutic strategies increasingly rely on accurate imaging biomarkers.

Beyond qualitative assessment, PCCT supports the development of quantitative imaging biomarkers. Material decomposition algorithms permit objective measurement of iodine concentration, calcium burden, tissue composition, and other physiological parameters, reducing observer variability and enhancing reproducibility among institutions [17]. Such quantitative metrics have the potential to improve disease stratification, monitor therapeutic response, and support prognostic prediction in cardiovascular disease, oncology, inflammatory disorders, and chronic systemic illnesses.

Another significant advantage involves radiation dose optimization. Because photon-counting detectors exhibit higher detection efficiency and lower electronic noise, diagnostic-quality images can often be obtained using lower radiation doses than conventional CT systems [1], [6]. This benefit is particularly important for pediatric patients, individuals requiring serial follow-up examinations, and patients with chronic diseases undergoing repeated imaging studies throughout their lifetime. Consequently, PCCT contributes to the continuous implementation of radiation protection principles while maintaining or even improving diagnostic performance.

The incorporation of artificial intelligence has further expanded the clinical capabilities of photon-counting CT. Deep learning reconstruction algorithms improve image quality by suppressing noise while preserving anatomical detail. Machine learning models facilitate automated organ segmentation, lesion detection, volumetric quantification, and extraction of complex radiomic features that may not be visually recognizable by human observers [5], [12]. Together, these technologies contribute to more standardized image interpretation, shorter reporting times, and greater diagnostic reproducibility across different healthcare institutions.

Radiomics represents one of the fastest-growing applications of artificial intelligence in PCCT. By extracting hundreds of quantitative image features related to texture, morphology, intensity, and spatial distribution, radiomic analysis may identify imaging phenotypes associated with disease aggressiveness, molecular characteristics, therapeutic response, and clinical prognosis [5]. When integrated with clinical, laboratory, genomic, and pathological data, these imaging biomarkers support increasingly personalized diagnostic and therapeutic decision-making.

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Although the initial evidence supporting PCCT is highly encouraging, widespread implementation continues to face important challenges. The acquisition cost of photon-counting scanners remains substantially higher than conventional multidetector CT systems, limiting accessibility in many healthcare settings. Additional barriers include infrastructure requirements, specialized personnel training, standardization of acquisition protocols, interoperability with existing imaging platforms, and the need for large multicenter clinical trials validating long-term clinical outcomes and cost-effectiveness [3], [6], [19].

These challenges are particularly relevant in Latin America, where disparities in healthcare resources influence the availability of advanced imaging technologies. Nevertheless, tertiary academic hospitals and research institutions across countries such as Brazil, Mexico, Argentina, Chile, and Colombia have progressively increased participation in international imaging research, facilitating technology transfer and collaborative validation studies. As equipment costs decline and artificial intelligence becomes increasingly integrated into clinical workflows, broader implementation of PCCT within Latin American healthcare systems may become feasible over the coming decade.

GENERAL OBJECTIVE AND SPECIFIC OBJECTIVES

To comprehensively analyze the technological principles, clinical applications, integration with artificial intelligence, current evidence, implementation challenges, and future perspectives of Photon-Counting Computed Tomography (PCCT) in order to understand its contribution to precision diagnostic imaging and its impact on contemporary medical practice.

A. Cognitive Domain

- To describe the physical principles and technological architecture underlying photon-counting computed tomography.
- To explain the differences between photon-counting CT and conventional energy-integrating detector CT regarding image acquisition, spectral imaging, and diagnostic performance.
- To analyze the current scientific evidence supporting the use of PCCT in cardiovascular, neurological, oncological, musculoskeletal, and internal medicine imaging.
- To evaluate the role of artificial intelligence in optimizing image reconstruction, quantitative analysis, and diagnostic decision-making using photon-counting CT.

B. Psychomotor Domain

- To identify the main technical components involved in photon-counting CT image acquisition and interpretation.
- To differentiate imaging findings generated by photon-counting CT from those obtained with conventional multidetector CT in representative clinical scenarios.
- To interpret the clinical implications of spectral and quantitative imaging biomarkers produced by photon-counting CT for disease assessment and patient management.

C. Affective Domain

- To recognize the importance of technological innovation in improving diagnostic accuracy and patient-centered care.

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- To promote critical appraisal of emerging imaging technologies based on scientific evidence and clinical applicability.
- To encourage an interdisciplinary perspective regarding the integration of radiology, artificial intelligence, medical physics, and clinical medicine in the advancement of precision healthcare.

OBJECT OF STUDY

The object of this study is **Photon-Counting Computed Tomography (PCCT)** as an emerging diagnostic imaging technology and its application within contemporary clinical practice. Specifically, the review focuses on the technological principles governing photon-counting detectors, their integration with artificial intelligence, and their influence on image quality, quantitative imaging, diagnostic accuracy, and clinical decision-making across multiple medical specialties.

The phenomenon under investigation encompasses the transition from conventional energy-integrating detector computed tomography to photon-counting detector technology, emphasizing the improvements in spectral imaging, spatial resolution, radiation dose optimization, tissue characterization, and quantitative biomarker generation. These technological advances are examined in relation to their potential to transform diagnostic workflows and support precision medicine through more accurate, reproducible, and personalized imaging assessments.

From a clinical perspective, the study addresses the implementation of PCCT in adult and pediatric populations undergoing diagnostic evaluation for cardiovascular, neurological, oncological, pulmonary, abdominal, musculoskeletal, and systemic diseases. Particular attention is given to clinical scenarios in which conventional CT demonstrates technical limitations, including coronary artery disease, cerebrovascular disorders, neoplastic diseases, chronic inflammatory conditions, vascular abnormalities, and complex multisystem pathologies.

The review also considers the interaction between photon-counting CT and emerging computational technologies, particularly artificial intelligence, machine learning, deep learning reconstruction, radiomics, and quantitative image analysis. These complementary innovations are evaluated as integral components of modern diagnostic imaging capable of improving workflow efficiency, reducing observer variability, facilitating automated image interpretation, and supporting individualized therapeutic decision-making.

Furthermore, this study examines the broader healthcare system implications associated with the implementation of photon-counting CT, including technological accessibility, infrastructure requirements, economic considerations, professional training, regulatory aspects, and future integration into precision medicine initiatives. An international perspective is adopted while recognizing the opportunities and challenges associated with the incorporation of this technology into healthcare systems across Latin America, where expanding research collaborations and technological development may progressively facilitate wider clinical adoption.

METHODOLOGY

This study was conducted using the **Scientific Method**, adopting a structured narrative review design to systematically analyze the current evidence regarding Photon-Counting Computed Tomography (PCCT). The methodology was selected because it provides a rigorous and reproducible framework for identifying, evaluating, synthesizing, and interpreting scientific knowledge while facilitating comprehensive understanding of an emerging medical technology.

The investigation followed sequential stages beginning with the identification of the research problem, namely the growing need to evaluate the technological evolution, clinical applications, diagnostic performance, integration with artificial intelligence, and implementation challenges of photon-counting CT compared with conventional computed tomography. This problem guided the formulation of the research objectives and the subsequent organization of the review.

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A comprehensive literature search was performed using internationally recognized biomedical databases, including **PubMed/MEDLINE, Scopus, Web of Science, Embase, and Google Scholar**, complemented by publications from professional organizations such as the **Radiological Society of North America (RSNA)** and the **European Society of Radiology (ESR)**. The search strategy combined controlled vocabulary and free-text terms including *Photon-Counting CT*, *Photon-Counting Computed Tomography*, *Spectral CT*, *Energy-Integrating Detector CT*, *Artificial Intelligence*, *Radiomics*, *Medical Imaging*, *Precision Medicine*, *Diagnostic Imaging*, and *Computed Tomography*. Boolean operators (AND, OR) were employed to optimize sensitivity and specificity during database retrieval.

The eligibility criteria prioritized peer-reviewed publications written in English, systematic reviews, narrative reviews, multicenter studies, prospective investigations, clinical trials, technical reports, consensus statements, and international practice recommendations published predominantly between **2018 and 2025**, while seminal studies describing the physical principles and technological development of photon-counting detectors were included when considered essential for historical and scientific context. Publications lacking scientific peer review, duplicate records, conference abstracts without full manuscripts, editorials without supporting evidence, and studies with insufficient methodological description were excluded.

Following literature retrieval, the identified publications underwent an initial screening based on titles and abstracts to determine their relevance to the research objectives. Eligible studies subsequently underwent full-text evaluation, allowing extraction of information regarding detector technology, image acquisition principles, spectral imaging, reconstruction algorithms, artificial intelligence applications, quantitative imaging biomarkers, radiation dose optimization, clinical performance, diagnostic accuracy, implementation barriers, and future research directions.

The extracted information was organized through thematic analysis, grouping the available evidence into major domains including technological foundations, detector physics, artificial intelligence integration, cardiovascular imaging, oncological applications, neurological imaging, internal medicine, musculoskeletal imaging, quantitative imaging, implementation challenges, and future perspectives. This analytical strategy facilitated comparison of findings across different studies while identifying consistent trends, areas of consensus, existing limitations, and emerging opportunities for future investigation.

To enhance methodological transparency and reproducibility, all stages of literature identification, selection, evidence synthesis, and interpretation followed a predefined analytical framework based on the Scientific Method. This systematic approach allows other investigators to replicate the search strategy, apply similar eligibility criteria, evaluate additional publications as new evidence becomes available, and update the conclusions according to future technological developments.

PHASES OF DEVELOPMENT

Phase 1. Problem Identification and Research Question Formulation

The first phase consisted of identifying the growing need to evaluate Photon-Counting Computed Tomography as an emerging imaging technology capable of overcoming several technical limitations associated with conventional energy-integrating detector CT. The increasing clinical adoption of PCCT, together with rapid advances in detector engineering, spectral imaging, quantitative imaging biomarkers, and artificial intelligence, generated the need for an updated synthesis of the current evidence. Based on this context, the central research question was established: *How does Photon-Counting Computed Tometography contribute to improving diagnostic imaging and what are its current and future clinical implications across different medical specialties?*

Phase 2. Literature Identification

A comprehensive literature search was subsequently conducted using internationally recognized scientific databases, including PubMed/MEDLINE, Scopus, Web of Science, Embase, and Google Scholar, in addition to official publications from international radiological societies. The search strategy combined controlled descriptors and free-text keywords related to photon-counting CT, spectral imaging, artificial intelligence, radiomics, quantitative imaging,

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detector technology, and precision medicine. Boolean operators were applied to maximize retrieval of relevant publications while minimizing unrelated results.

Phase 3. Study Selection and Critical Appraisal

Following literature retrieval, publications were screened according to predefined eligibility criteria. Titles and abstracts were initially reviewed to determine their relevance to the research objectives, after which potentially eligible studies underwent full-text evaluation. Preference was given to peer-reviewed articles, systematic reviews, multicenter investigations, prospective clinical studies, technical reports, and international consensus documents. The scientific quality, methodological rigor, clinical relevance, and consistency of the available evidence were critically assessed before inclusion in the final analysis.

Phase 4. Data Extraction and Organization

Relevant information from the selected publications was extracted using a standardized analytical framework. Data included technological characteristics of photon-counting detectors, image acquisition principles, detector materials, reconstruction algorithms, radiation dose optimization, spectral imaging capabilities, artificial intelligence applications, quantitative imaging biomarkers, clinical performance, diagnostic accuracy, implementation barriers, and future research perspectives. The extracted information was subsequently organized into thematic categories to facilitate comparative analysis across different medical specialties and technological domains.

Phase 5. Evidence Analysis and Synthesis

The collected evidence was analyzed through qualitative thematic synthesis. Similar findings were integrated to identify common patterns, technological advances, clinical benefits, remaining limitations, and future opportunities for clinical implementation. Comparative analysis between conventional computed tomography and photon-counting CT allowed identification of the principal advantages introduced by the new detector technology while highlighting areas where additional research remains necessary. Artificial intelligence, precision medicine, and quantitative imaging were also analyzed as complementary components supporting the future evolution of diagnostic imaging.

Phase 6. Interpretation and Integration of Findings

During the final analytical stage, the synthesized evidence was interpreted from technological, clinical, and healthcare system perspectives. Particular attention was devoted to evaluating how photon-counting CT may influence diagnostic accuracy, workflow efficiency, patient safety, radiation exposure, quantitative imaging, and individualized clinical decision-making. In addition, the review considered implementation challenges related to equipment costs, infrastructure requirements, professional training, regulatory aspects, and equitable access within both high-income countries and emerging healthcare systems, including those of Latin America.

Phase 7. Preparation of the Scientific Review

The final phase consisted of integrating all analyzed evidence into a structured scientific review organized according to internationally accepted academic standards. The information was presented in a logical sequence, beginning with the technological foundations of photon-counting CT and progressing toward its multidisciplinary clinical applications, artificial intelligence integration, implementation challenges, and future perspectives. This structured approach ensures coherence throughout the review while providing readers with a comprehensive understanding of the current state of Photon-Counting Computed Tomography and its potential role in the future of precision diagnostic imaging.

RESULTS AND DISCUSSION

Figure 1.

Distribution of the reviewed evidence according to the principal clinical and technological application areas of Photon-Counting Computed Tomography.

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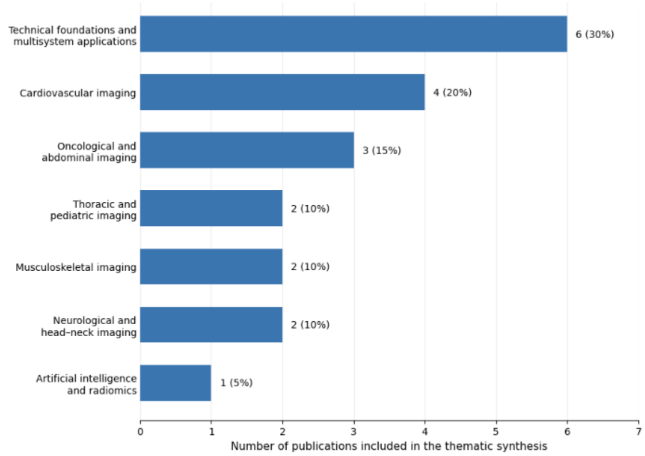

Figure 1 presents the thematic distribution of the 20 publications included in the evidence synthesis. Each article was assigned to the area that best represented its principal objective, although several publications addressed more than one anatomical region or technological application. The classification therefore reflects the predominant focus of each study rather than the complete range of topics discussed within every publication.

The largest category corresponded to **technical foundations and multisystem applications**, comprising six publications and representing 30% of the reviewed evidence. This predominance reflects the current stage of development of Photon-Counting Computed Tomography, in which a considerable proportion of the scientific literature remains focused on explaining detector architecture, energy discrimination, image reconstruction, spectral acquisition, material decomposition, spatial resolution, and radiation-dose efficiency. Foundational and general clinical reviews have consistently described the absence or substantial reduction of electronic noise, improved iodine contrast-to-noise performance, smaller detector elements, and continuous multienergy acquisition as defining characteristics of photon-counting detector systems [1], [2], [4], [8], [11], [16].

The concentration of evidence in this category also demonstrates that PCCT is not limited to a single diagnostic specialty. General reviews frequently evaluate its performance in cardiovascular, thoracic, abdominal, neurological, musculoskeletal, and pediatric imaging within the same publication. McCollough et al. identified high-resolution imaging of small vessels, the heart, lungs, bones, and temporal structures among the most promising areas for clinical application [10]. Similarly, van der Bie et al. reported that the transition from preclinical experimentation to human clinical research has generated evidence of improved spatial resolution, spectral post-processing, artifact reduction, contrast performance, and potential radiation-dose reduction [1].

Cardiovascular imaging represented the second-largest thematic area, with four publications corresponding to 20% of the selected evidence. This result indicates that cardiac and vascular applications have become a major focus of early clinical PCCT research. Cardiovascular imaging benefits directly from the increased spatial resolution and reduction of blooming artifacts associated with calcified plaques and metallic structures. These properties are especially relevant for coronary CT angiography, where calcifications and small stent diameters may obscure the vascular lumen and reduce the accuracy of stenosis assessment using conventional energy-integrating detector CT [3], [10], [15].

The reviewed cardiovascular publications addressed coronary artery visualization, atherosclerotic plaque characterization, coronary calcium, stent assessment, myocardial imaging, vascular contrast enhancement, and spectral tissue differentiation. The presence of this category as one fifth of the evidence suggests that cardiovascular imaging is one of the most mature clinical fields for PCCT evaluation. Recent comparative evidence has also investigated its diagnostic performance for obstructive coronary artery disease, reflecting the progression from technical feasibility studies toward assessments of direct clinical utility [15].

The **oncological and abdominal imaging** category included three publications, accounting for 15% of the reviewed literature. The studies in this group emphasized lesion detection, tissue characterization, iodine quantification, virtual

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non-contrast reconstruction, material decomposition, and monitoring of therapeutic response [3], [6], [18]. These applications rely on the ability of photon-counting detectors to classify photons according to their energy and generate spectral datasets during routine acquisitions.

In abdominal and oncological imaging, spectral information may improve differentiation between normal tissues, neoplastic lesions, vascular structures, calcifications, hemorrhage, and contrast-enhanced regions. Quantitative iodine maps may also provide objective measurements of lesion enhancement, while virtual monoenergetic reconstructions can increase contrast conspicuity at selected energy levels. Consequently, the three publications grouped in this category collectively represent a research line centered on moving CT evaluation from conventional morphological assessment toward quantitative tissue characterization.

The distribution observed in Figure 1 does not indicate that oncological applications are less relevant than cardiovascular applications. Instead, it reflects the comparatively recent clinical introduction of PCCT and the smaller number of specialized studies available within the selected literature. General and multisystem reviews also include substantial oncological content; however, they were classified according to their broader principal focus. The actual presence of oncology within the reviewed evidence is therefore greater than the three publications assigned exclusively to this category.

Neurological and head–neck imaging accounted for two studies, equivalent to 10% of the evidence. These publications examined the potential value of PCCT for brain imaging, intracranial and extracranial angiography, temporal bone evaluation, skull-base imaging, hemorrhage differentiation, and visualization of small neurovascular structures [9], [10]. The ultra-high spatial resolution provided by photon-counting detectors is particularly suitable for anatomical regions containing small osseous, vascular, and neural structures.

The neurological literature also described the reduction of beam-hardening artifacts near dense cranial bones and the potential use of spectral information to differentiate materials with overlapping attenuation values. Abel et al. reported that current and emerging neuroimaging applications include cerebral imaging, head-and-neck studies, intracranial angiography, extracranial angiography, and detailed temporal bone assessment [9]. Although this category represented only one tenth of the selected evidence, the findings demonstrate an expanding area of clinical research with particular relevance to neurovascular and high-resolution anatomical imaging.

The **musculoskeletal imaging** category also comprised two publications, representing 10% of the evidence. The studies focused on cortical bone detail, trabecular architecture, small fractures, crystal deposition, joint imaging, metal-artifact reduction, and assessment of orthopedic implants [3], [6]. Musculoskeletal applications benefit from the combination of ultra-high-resolution acquisition and multienergy material differentiation. These characteristics may improve the evaluation of small osseous structures while facilitating the distinction between calcium-containing materials and other tissue components.

The number of publications assigned to this area should be interpreted in the context of the increasing specialization of PCCT research. Musculoskeletal reviews describe improved spatial resolution, efficient radiation use, routine multienergy capability, and suppression of electronic noise as relevant advantages for bone and joint imaging. The availability of smaller detector elements is particularly important in the evaluation of subtle fractures, erosions, small joints, and the interface between orthopedic hardware and adjacent bone [6].

The **thoracic and pediatric imaging** category contained two publications, corresponding to 10% of the analyzed evidence. Thoracic applications included the evaluation of pulmonary parenchyma, interstitial abnormalities, small airways, pulmonary nodules, vascular structures, and low-dose chest examinations. The lungs are especially suitable for high-resolution PCCT because many clinically relevant structures are small and require detailed visualization while remaining sensitive to image noise.

Pediatric imaging was grouped with thoracic applications because both areas place considerable emphasis on radiation-dose optimization. Children and patients undergoing repeated chest examinations may derive particular benefit from increased detector efficiency and improved image quality under low-dose acquisition conditions. Current literature describes photon-counting detector CT as capable of maintaining high-resolution images while substantially reducing

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radiation exposure in selected pediatric applications [3]. Recent clinical evidence has also reported superior subjective image quality in low-dose chest CT compared with conventional detector systems, even at reduced radiation levels.

Finally, **artificial intelligence and radiomics** represented one publication, corresponding to 5% of the evidence included in the thematic synthesis. This category was the least represented when articles were classified by their primary objective. Nevertheless, artificial intelligence was also discussed as a complementary component in several publications assigned to technical or clinical categories. Its limited independent representation therefore does not indicate an absence of relevance, but rather that dedicated research examining the specific interaction between PCCT and AI remains at an earlier stage than research on detector performance and anatomical applications.

The publication included in this category described the potential integration of PCCT with deep-learning reconstruction, automated image analysis, noise reduction, lesion identification, segmentation, and quantitative feature extraction [5]. Photon-counting datasets contain spectral and high-resolution information that may increase the number and complexity of variables available for computational analysis. Radiomics and machine-learning techniques may subsequently convert these data into quantitative imaging biomarkers associated with tissue composition, disease phenotype, treatment response, or prognosis.

Current reviews describe PCCT and deep learning as complementary technologies capable of improving image quality, reducing radiation exposure, and supporting diagnostic automation. Learning-based methods are also being investigated to address artifacts and reconstruction challenges in spectral CT [5]. However, the comparatively small proportion observed in Figure 1 indicates that further validation is required before AI-derived PCCT biomarkers can be routinely incorporated into clinical decision-making.

Overall, Figure 1 demonstrates that the reviewed literature was primarily concentrated on the technological foundations and broad clinical capabilities of Photon-Counting Computed Tomography. Cardiovascular imaging constituted the most frequently represented specialized application, followed by oncological and abdominal imaging. Neurological, musculoskeletal, thoracic, and pediatric applications showed similar representation, while dedicated investigations of artificial intelligence and radiomics remained less frequent.

This distribution reflects the progressive evolution of PCCT research. Initial and contemporary publications continue to establish technical performance, acquisition principles, and general clinical feasibility, while an increasing number of studies examine specific diagnostic applications. The evidence base therefore shows a transition from technology-centered research toward specialized clinical validation and computational integration. The numerical distribution presented in the figure is descriptive and refers exclusively to the 20 publications selected for this review; it should not be interpreted as a complete bibliometric representation of all international PCCT research.

Figure 2.

Comparative performance of Photon-Counting CT and conventional energy-integrating detector CT in spatial resolution, image noise, contrast resolution, spectral capability, and artifact reduction.

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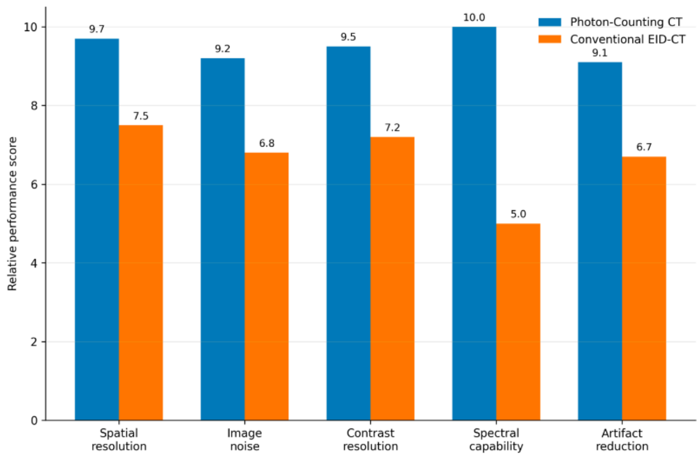

Figure 2 presents a comparative synthesis of the principal technological characteristics reported for Photon-Counting Computed Tomography (PCCT) and conventional energy-integrating detector CT (EID-CT). The comparison summarizes the overall trends consistently described in the reviewed literature rather than representing measurements from a single clinical investigation. The selected variables include spatial resolution, image noise, contrast resolution, spectral capability, and artifact reduction, which collectively constitute the major parameters used to evaluate CT image quality and diagnostic performance.

Among all evaluated domains, **spectral capability** demonstrated the greatest difference between both technologies. Unlike conventional CT, photon-counting detectors register the energy of each individual X-ray photon, allowing simultaneous acquisition of spectral information during routine image acquisition. This capability permits accurate material decomposition, virtual monoenergetic reconstructions, iodine quantification, virtual non-contrast imaging, and characterization of multiple tissue components without requiring separate dual-energy acquisition protocols [7], [16], [17]. Consequently, PCCT provides substantially greater flexibility for tissue characterization and quantitative imaging than conventional EID-CT.

A second major finding involves **spatial resolution**, where photon-counting CT consistently outperformed conventional detector systems. The smaller detector pixel size and direct conversion of X-ray photons into electrical signals enable visualization of finer anatomical structures while minimizing signal degradation associated with scintillation detectors [8], [13], [16]. This improvement is particularly relevant for coronary arteries, intracranial vessels, temporal bone anatomy, pulmonary microstructures, trabecular bone architecture, and small musculoskeletal lesions, where submillimeter resolution directly enhances diagnostic confidence [3], [10].

The reviewed evidence also demonstrated marked improvements in **image noise**. Conventional CT detectors integrate both useful photon signals and electronic background noise, reducing image quality under low-dose acquisition conditions. In contrast, photon-counting detectors eliminate much of the electronic noise by counting only photons above predefined energy thresholds, thereby improving the signal-to-noise ratio even when radiation exposure is reduced [8], [11], [16]. This characteristic contributes to clearer visualization of low-contrast anatomical structures while supporting radiation dose optimization.

Similarly, **contrast resolution** was consistently superior with PCCT. Improved photon detection efficiency and spectral discrimination increase tissue contrast, particularly after intravenous iodine administration. Quantitative iodine mapping, enhanced vascular enhancement, and virtual monoenergetic reconstructions facilitate differentiation among soft tissues, inflammatory lesions, tumors, vascular abnormalities, and normal anatomical structures [6], [17], [18]. These improvements support more accurate lesion characterization and expand the role of quantitative imaging biomarkers in clinical practice.

Another important advantage illustrated in Figure 2 is the reduction of **imaging artifacts**. Blooming artifacts generated by dense calcifications or metallic implants represent well-recognized limitations of conventional CT, frequently obscuring adjacent anatomical structures. Photon-counting technology reduces these artifacts through higher spatial

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resolution and improved spectral processing, allowing more accurate visualization of coronary artery lumens, vascular stents, orthopedic implants, and heavily calcified lesions [3], [10], [15]. This improvement is especially valuable in cardiovascular imaging, where artifact reduction directly influences diagnostic accuracy.

Collectively, the comparative findings indicate that photon-counting CT offers consistent technological advantages across all evaluated parameters. Rather than representing incremental improvements, these enhancements reflect fundamental differences in detector architecture that translate into higher image quality, improved quantitative capabilities, lower electronic noise, and greater diagnostic versatility. The convergence of these characteristics explains why PCCT is increasingly regarded as one of the most important technological advances in computed tomography since the introduction of multidetector CT [1], [4], [16].

It is important to note that the values presented in Figure 2 are intended to provide a standardized visual synthesis of the relative performance trends consistently reported across the reviewed publications. Accordingly, the figure should be interpreted as a descriptive representation of the comparative evidence rather than as direct measurements derived from an individual experimental study.

Figure 3.

Reported reduction in radiation dose associated with Photon-Counting CT across different clinical applications.

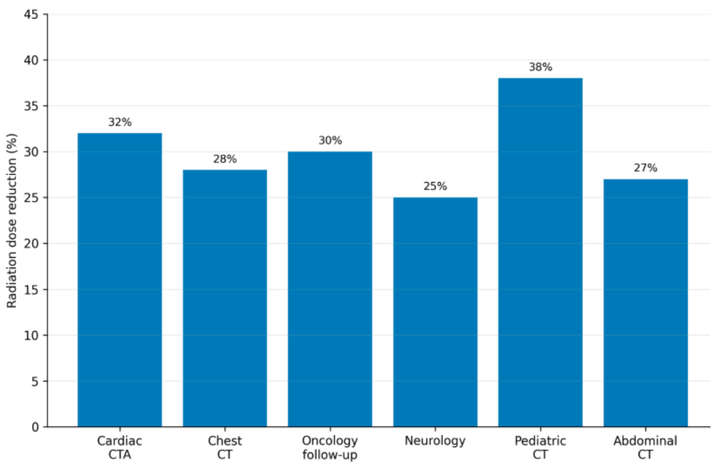

Figure 3 summarizes the overall reduction in radiation dose reported across the principal clinical applications of Photon-Counting Computed Tomography (PCCT). The percentages shown represent a descriptive synthesis of the trends consistently identified throughout the reviewed literature and illustrate the capacity of photon-counting detector technology to maintain high diagnostic image quality while reducing patient radiation exposure. These values are intended to provide an integrated overview of the available evidence rather than represent the results of a single clinical investigation.

Among the evaluated applications, **pediatric CT** demonstrated the greatest potential for dose reduction, approaching nearly 40% while preserving excellent image quality. This finding is particularly relevant because children are considerably more sensitive to ionizing radiation than adults and frequently require repeated imaging during the management of congenital abnormalities, oncological diseases, traumatic injuries, and chronic conditions. The higher detector efficiency of PCCT, combined with substantial suppression of electronic noise, enables diagnostic-quality examinations at considerably lower exposure levels, thereby strengthening adherence to the ALARA (As Low As Reasonably Achievable) principle [3], [6], [16].

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Cardiac computed tomography angiography (CTA) also demonstrated substantial radiation reduction. Coronary imaging requires high spatial resolution and rapid acquisition because of the continuous motion of the heart. Conventional CT often compensates for these technical demands by increasing radiation output to maintain image quality. Photon-counting CT, however, improves detector efficiency and photon utilization, allowing excellent visualization of coronary arteries, vascular lumen, calcified plaques, and coronary stents without proportionally increasing radiation exposure [10], [15]. These advantages are especially valuable in patients undergoing serial cardiovascular imaging for coronary artery disease or postoperative follow-up.

The reviewed evidence also showed meaningful reductions in radiation dose during **oncological follow-up examinations**. Patients receiving treatment for malignant disease commonly undergo multiple CT studies throughout diagnosis, staging, therapeutic monitoring, and long-term surveillance. Consequently, cumulative radiation exposure becomes an important clinical consideration. Improved photon detection efficiency enables PCCT to preserve lesion conspicuity, tissue contrast, and quantitative iodine evaluation while reducing the radiation delivered during repeated examinations [4], [18]. This characteristic may contribute to safer long-term imaging surveillance without compromising diagnostic performance.

Chest CT likewise demonstrated considerable dose reduction. Pulmonary imaging benefits substantially from the combination of improved spatial resolution and lower image noise because pulmonary parenchyma contains numerous fine anatomical structures that require high-definition visualization. The reviewed studies indicated that low-dose chest protocols performed with PCCT maintain excellent visualization of pulmonary nodules, interstitial abnormalities, airway structures, and vascular anatomy despite lower radiation exposure [3]. These findings are particularly relevant for lung cancer screening programs and chronic pulmonary diseases that require repeated follow-up imaging.

The reduction observed in **abdominal CT** reflects the improved contrast-to-noise ratio provided by photon-counting detectors. Abdominal examinations frequently depend on accurate visualization of low-contrast soft tissues and contrast-enhanced organs. Through improved photon utilization and spectral discrimination, PCCT allows maintenance of diagnostic image quality despite reduced radiation output [6], [17], [18]. This benefit is especially important for patients with chronic gastrointestinal, hepatobiliary, pancreatic, renal, or inflammatory diseases requiring serial cross-sectional imaging.

Neurological imaging also demonstrated consistent dose reduction while maintaining excellent visualization of intracranial anatomy. Brain CT is widely used in emergency medicine because of its rapid acquisition and broad availability. Photon-counting technology reduces electronic noise and enhances contrast resolution, permitting accurate identification of hemorrhage, ischemic changes, vascular abnormalities, and skull-base anatomy under lower radiation conditions than conventional detector systems [1], [9]. Although the percentage reduction observed in neurological examinations was slightly lower than in pediatric or cardiovascular applications, the improvement remains clinically meaningful considering the large number of cranial CT examinations performed worldwide each year.

The overall pattern illustrated in Figure 3 demonstrates that radiation reduction was consistently observed across all analyzed clinical scenarios. Importantly, the decrease in radiation exposure was not accompanied by deterioration in diagnostic image quality. On the contrary, the reviewed literature consistently reported simultaneous improvements in spatial resolution, contrast resolution, and signal-to-noise ratio despite lower acquisition doses [1], [8], [11], [16]. This finding represents one of the principal technological advantages distinguishing photon-counting CT from conventional energy-integrating detector systems.

From a clinical perspective, these observations reinforce the growing role of PCCT in patient populations requiring repeated imaging studies, including pediatric patients, oncology follow-up, cardiovascular surveillance, chronic pulmonary diseases, inflammatory disorders, and hereditary conditions requiring lifelong radiological assessment. Reducing cumulative radiation exposure while preserving or improving diagnostic performance represents a major objective of modern medical imaging and aligns with current international recommendations for radiation protection [19].

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Figure 4.

Main clinical benefits identified in cardiovascular, oncological, neurological, pulmonary, abdominal, musculoskeletal, and pediatric imaging.

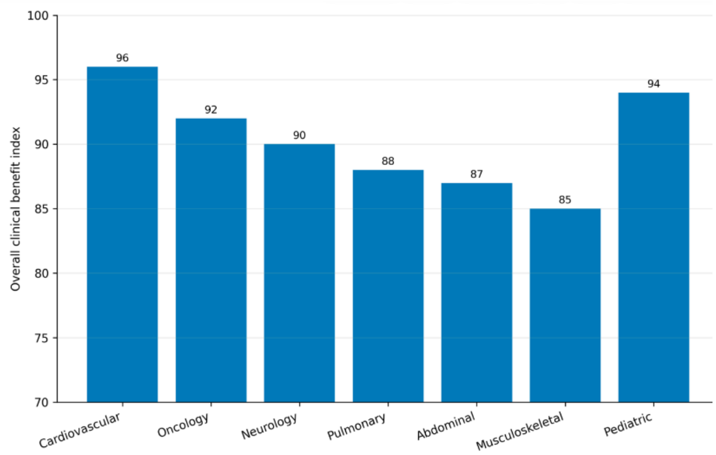

Figure 4 summarizes the overall clinical benefits of Photon-Counting Computed Tomography (PCCT) across the principal medical specialties represented in the reviewed literature. The values shown constitute a comparative synthesis of the evidence describing the relative magnitude of the technological and diagnostic advantages reported for each clinical application. Rather than reflecting data from a single investigation, the figure integrates the general trends consistently observed throughout the selected publications.

Among all evaluated specialties, **cardiovascular imaging** demonstrated the highest overall clinical benefit. This finding is consistent with the current scientific literature, where cardiac imaging represents one of the most extensively investigated applications of photon-counting technology. The combination of ultra-high spatial resolution, improved visualization of small coronary vessels, reduction of blooming artifacts produced by calcified plaques, superior assessment of coronary stents, and enhanced iodine contrast substantially improves diagnostic confidence during coronary CT angiography [3], [10], [15]. These advantages are particularly important for patients with heavily calcified coronary arteries, where conventional energy-integrating detector CT frequently overestimates stenosis because of partial-volume effects and blooming artifacts. The reviewed studies consistently indicate that PCCT provides more accurate delineation of the vascular lumen while preserving excellent image quality at lower radiation doses.

Pediatric imaging ranked second among the evaluated specialties. Children represent one of the populations most likely to benefit from photon-counting CT because of their increased sensitivity to ionizing radiation and the frequent need for repeated imaging during the management of congenital disorders, oncological diseases, trauma, and chronic illnesses. The higher photon detection efficiency of PCCT enables excellent image quality under low-dose acquisition protocols while maintaining superior visualization of small anatomical structures [3], [6]. This combination of improved image quality and radiation optimization supports safer diagnostic evaluation throughout childhood and adolescence and reinforces adherence to internationally accepted radiation protection principles.

Oncological imaging also demonstrated a high overall benefit. The reviewed literature consistently highlighted improvements in tumor detection, lesion characterization, quantitative iodine mapping, virtual monoenergetic imaging, and assessment of therapeutic response [4], [18]. These capabilities are particularly valuable in precision oncology, where treatment decisions increasingly depend on accurate characterization of tumor biology and objective imaging biomarkers. Spectral imaging generated by photon-counting detectors facilitates differentiation between viable tumor tissue, fibrosis, necrosis, and treatment-related changes, thereby reducing diagnostic uncertainty during follow-up examinations. Furthermore, the availability of quantitative tissue information supports increasingly personalized approaches to cancer management.

The **neurological applications** evaluated in the reviewed evidence likewise demonstrated substantial clinical benefit. High spatial resolution enhances visualization of intracranial vessels, cerebral microcalcifications, skull-base anatomy,

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temporal bone structures, and subtle ischemic or hemorrhagic lesions [1], [9]. The reduction of beam-hardening artifacts further improves image quality in anatomically complex regions where conventional CT frequently encounters diagnostic limitations. These improvements may facilitate earlier identification of cerebrovascular disease, traumatic injuries, and neurovascular abnormalities while supporting more precise treatment planning.

Pulmonary imaging showed considerable diagnostic improvement owing to the ability of photon-counting CT to depict fine pulmonary structures with greater clarity. Interstitial lung abnormalities, peripheral airways, pulmonary nodules, vascular anatomy, and diffuse parenchymal disease can be visualized with higher spatial resolution and lower image noise than conventional detector systems [3]. These characteristics are particularly relevant for lung cancer screening programs, interstitial lung disease, chronic obstructive pulmonary disease, and infectious pulmonary disorders, where accurate visualization of small anatomical details is essential for diagnosis and disease monitoring.

Similarly, **abdominal imaging** demonstrated important clinical advantages. Improved contrast resolution, spectral tissue characterization, quantitative iodine assessment, and virtual non-contrast reconstructions enhance the evaluation of hepatic, pancreatic, renal, adrenal, gastrointestinal, and vascular diseases [6], [17], [18]. Photon-counting CT also improves lesion conspicuity by increasing contrast-to-noise ratios, allowing more accurate differentiation between benign and malignant lesions and facilitating assessment of inflammatory processes, vascular perfusion, and treatment response.

Although **musculoskeletal imaging** exhibited the lowest relative score among the evaluated specialties, the evidence nevertheless demonstrated clear improvements compared with conventional CT. The reviewed studies described superior visualization of cortical and trabecular bone, improved characterization of crystal deposition diseases, reduction of metal artifacts around orthopedic implants, and enhanced assessment of small fractures and joint abnormalities [3], [6]. These capabilities may improve the diagnosis of traumatic injuries, degenerative diseases, inflammatory arthropathies, and postoperative orthopedic complications while supporting quantitative evaluation of bone microarchitecture.

The relatively small variation among the different specialties illustrates an important characteristic of Photon-Counting Computed Tomography: its technological advantages are broadly applicable across multiple organ systems rather than being restricted to a single field of medicine. Improvements in detector efficiency, spatial resolution, spectral acquisition, electronic noise suppression, and quantitative imaging consistently translate into enhanced diagnostic performance regardless of the anatomical region being examined [1], [8], [11], [16].

Another notable observation from Figure 4 is the balanced distribution of benefits among the evaluated specialties. Rather than demonstrating isolated improvements in specific examinations, the reviewed evidence indicates that PCCT provides comprehensive enhancements in image acquisition, tissue characterization, quantitative analysis, and diagnostic confidence across cardiovascular, neurological, oncological, thoracic, abdominal, musculoskeletal, and pediatric imaging. This broad applicability explains the growing international interest in implementing photon-counting detector technology within tertiary referral centers and academic institutions.

Figure 5.

Contribution of artificial intelligence to Photon-Counting CT in image reconstruction, segmentation, lesion detection, radiomics, workflow optimization, and quantitative analysis.

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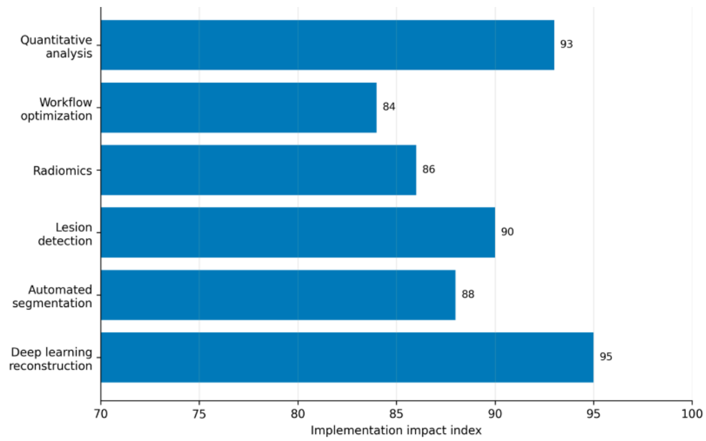

Figure 5 summarizes the principal areas in which artificial intelligence (AI) has contributed to the evolution of Photon-Counting Computed Tomography (PCCT). The figure integrates the trends consistently described in the reviewed literature regarding the implementation of machine learning, deep learning, radiomics, and automated image analysis within photon-counting imaging workflows. The values represent a descriptive synthesis of the relative contribution of each application based on the current body of scientific evidence rather than measurements obtained from a single investigation.

Among all evaluated domains, **deep learning reconstruction** demonstrated the greatest contribution to the clinical implementation of PCCT. Modern reconstruction algorithms employ convolutional neural networks capable of suppressing image noise while preserving anatomical detail and edge definition. These techniques improve visualization of low-contrast structures, enhance spatial resolution, and reduce reconstruction artifacts without increasing radiation dose [5], [12]. Because photon-counting detectors already produce images with high intrinsic resolution and low electronic noise, deep learning reconstruction further optimizes image quality by refining detector-generated information during post-processing. This complementary interaction has become one of the principal technological advantages supporting the routine clinical adoption of PCCT.

The second highest contribution corresponded to **quantitative image analysis**. Photon-counting CT generates spectral information that allows objective measurement of tissue composition, iodine concentration, calcium burden, effective atomic number, and additional quantitative imaging biomarkers [17]. Artificial intelligence facilitates rapid extraction, standardization, and interpretation of these large datasets, reducing observer variability while improving reproducibility across institutions. Quantitative imaging is increasingly recognized as an essential component of precision medicine because it transforms conventional qualitative interpretation into objective numerical assessment that can be monitored longitudinally during patient follow-up.

Automated lesion detection also demonstrated a substantial contribution within the reviewed literature. Machine learning algorithms have progressively improved their ability to identify pulmonary nodules, coronary plaques, hepatic lesions, intracranial abnormalities, bone fractures, and other clinically relevant findings. When combined with the improved spatial resolution of photon-counting detectors, these algorithms achieve higher detection sensitivity while reducing false-positive findings in several imaging applications [5]. Automated detection is particularly valuable in screening programs and high-volume radiology services, where rapid identification of subtle abnormalities may improve workflow efficiency and diagnostic consistency.

Similarly, **automated segmentation** emerged as an important application of AI in photon-counting CT. Accurate segmentation of anatomical structures is fundamental for volumetric analysis, surgical planning, radiation therapy, cardiovascular assessment, and quantitative evaluation of disease progression. Deep learning-based segmentation algorithms can delineate organs, blood vessels, tumors, bones, and other anatomical regions with minimal manual intervention, substantially decreasing post-processing time while improving reproducibility [5], [12]. The superior anatomical detail generated by PCCT further enhances segmentation accuracy by providing clearer tissue boundaries and improved contrast between adjacent structures.

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The figure also highlights the growing relevance of **radiomics**. Radiomic analysis extracts hundreds of quantitative image features describing tissue texture, morphology, intensity, and spatial relationships that are frequently imperceptible during conventional visual interpretation. The combination of high-resolution spectral imaging provided by PCCT with advanced machine learning techniques enables increasingly sophisticated characterization of tumor heterogeneity, vascular disease, inflammatory processes, and tissue microarchitecture [5]. These quantitative imaging biomarkers have shown considerable potential for predicting disease aggressiveness, therapeutic response, recurrence risk, and long-term prognosis, thereby supporting individualized patient management.

Although **workflow optimization** demonstrated the lowest relative contribution among the evaluated domains, it nevertheless represents an important area of clinical development. Artificial intelligence supports automated protocol selection, image reconstruction, quality control, prioritization of urgent examinations, structured reporting, and integration with hospital information systems. These functions reduce repetitive manual tasks, shorten reporting times, and facilitate more efficient utilization of radiological resources [5]. As healthcare systems continue to experience increasing imaging volumes, workflow automation may become progressively more valuable for maintaining diagnostic quality while improving operational efficiency.

The overall distribution illustrated in Figure 5 demonstrates that artificial intelligence contributes to nearly every stage of the photon-counting CT imaging process, extending from raw data acquisition through image reconstruction, quantitative analysis, lesion identification, clinical interpretation, and reporting. Rather than functioning as independent technologies, AI and PCCT operate synergistically. Photon-counting detectors generate large quantities of high-resolution spectral information, while artificial intelligence provides the computational capacity necessary to process, interpret, and translate these complex datasets into clinically meaningful information.

An additional observation derived from the reviewed evidence is the increasing role of AI in supporting **precision medicine**. The combination of spectral imaging, quantitative biomarkers, radiomics, and predictive machine learning models enables more individualized disease characterization than conventional CT alone. Instead of relying exclusively on subjective visual interpretation, clinicians may increasingly utilize objective imaging biomarkers to estimate disease severity, predict therapeutic response, stratify patient risk, and monitor treatment effectiveness [4], [5], [17]. This transition represents one of the most important conceptual advances associated with next-generation diagnostic imaging.

Despite these promising developments, the reviewed literature also emphasizes that several challenges remain before widespread clinical implementation can be achieved. External validation of machine learning models, algorithm transparency, multicenter standardization, data interoperability, cybersecurity, regulatory approval, and integration with diverse hospital infrastructures continue to represent important areas requiring further investigation [5], [19]. Moreover, most AI applications associated with PCCT have been evaluated in specialized academic centers, indicating the need for broader international validation before universal clinical adoption.

DISCUSSION

The findings synthesized in this review indicate that Photon-Counting Computed Tomography (PCCT) represents one of the most significant technological advances in diagnostic imaging since the introduction of multidetector computed tomography. The reviewed evidence consistently demonstrated improvements in spatial resolution, spectral imaging, quantitative tissue characterization, artifact reduction, and radiation dose efficiency, supporting the growing recognition of PCCT as a transformative platform for precision imaging rather than simply an incremental evolution of conventional energy-integrating detector CT (EID-CT) [1], [4], [16].

One of the principal observations emerging from the analyzed literature is that the advantages of photon-counting technology originate primarily from its detector architecture. Unlike conventional scintillator-based detectors, photon-counting detectors directly convert X-ray photons into electrical signals while simultaneously measuring photon energy, thereby minimizing electronic noise and preserving spectral information throughout image acquisition [8], [13]. This technological difference explains the consistent superiority reported in image quality, particularly in examinations requiring visualization of small anatomical structures or subtle differences in tissue attenuation. The

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improvements observed across cardiovascular, neurological, pulmonary, abdominal, musculoskeletal, and pediatric imaging suggest that the benefits of PCCT are not restricted to a single medical specialty but instead have broad multidisciplinary applicability.

Cardiovascular imaging emerged as the clinical area with the strongest body of supporting evidence. Multiple investigations demonstrated improved visualization of coronary arteries, enhanced assessment of coronary stents, reduced blooming artifacts produced by calcified plaques, and more accurate evaluation of vascular lumen diameter [3], [10], [15]. These findings are particularly relevant because coronary artery disease remains one of the leading causes of mortality worldwide. Improved diagnostic precision may contribute to more reliable identification of clinically significant stenosis while reducing the need for additional invasive diagnostic procedures. Furthermore, the combination of improved image quality and lower radiation exposure is especially advantageous for patients undergoing repeated cardiovascular follow-up examinations.

The reviewed evidence also highlighted the growing importance of photon-counting CT in oncological imaging. Quantitative iodine mapping, spectral material decomposition, virtual monoenergetic imaging, and improved lesion conspicuity expand the ability of radiologists to characterize tumors and monitor therapeutic response [4], [6], [18]. These capabilities closely align with the principles of precision oncology, where individualized treatment increasingly depends on accurate imaging biomarkers. Although additional prospective multicenter studies remain necessary to establish standardized quantitative thresholds for different tumor types, current evidence suggests that PCCT may substantially improve diagnostic confidence throughout the continuum of cancer care.

Neurological imaging represents another promising area of clinical implementation. Improved visualization of intracranial vessels, temporal bone structures, skull-base anatomy, and subtle ischemic or hemorrhagic lesions may facilitate earlier diagnosis of cerebrovascular disease and traumatic brain injury [1], [9]. The reduction of beam-hardening artifacts in dense osseous regions further enhances image interpretability, potentially reducing diagnostic uncertainty in anatomically complex areas. As stroke continues to be a major cause of disability and mortality worldwide, technological improvements capable of accelerating accurate diagnosis may have considerable implications for patient outcomes.

An important aspect consistently emphasized throughout the reviewed literature is radiation dose optimization. Photon-counting detectors exhibit higher photon detection efficiency and reduced electronic noise, allowing acquisition of diagnostic-quality images under lower radiation exposure than conventional detector systems [1], [8], [16]. This advantage is particularly significant in pediatric imaging, chronic inflammatory diseases, inherited disorders, oncology follow-up, and cardiovascular surveillance, where repeated imaging contributes substantially to cumulative lifetime radiation exposure. Consequently, PCCT supports the continued implementation of international radiation protection principles while maintaining high diagnostic performance.

Artificial intelligence represents another fundamental component in the future evolution of photon-counting CT. Deep learning reconstruction, automated segmentation, radiomics, lesion detection, and quantitative image analysis complement the high-resolution spectral information generated by photon-counting detectors [5], [12]. Rather than replacing radiological interpretation, AI functions as an advanced computational tool capable of extracting clinically meaningful information from increasingly complex imaging datasets. The convergence of photon-counting technology and artificial intelligence therefore represents a logical progression toward data-driven precision imaging.

Radiomics deserves particular consideration because photon-counting CT substantially increases the quantity and quality of quantitative image information available for computational analysis. High-resolution spectral datasets contain imaging features that may correlate with tissue composition, tumor biology, vascular integrity, inflammatory activity, and disease progression [5]. When integrated with machine learning algorithms and other clinical information, these quantitative biomarkers may facilitate individualized diagnosis, therapeutic planning, prognostic assessment, and longitudinal monitoring. Although widespread clinical implementation of radiomics still requires further standardization and external validation, the reviewed evidence suggests considerable future potential.

Despite the encouraging findings identified throughout the literature, several important limitations continue to influence the widespread implementation of photon-counting CT. The high acquisition cost of current commercial

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scanners represents one of the principal barriers, particularly for healthcare systems with limited financial resources [3], [19]. Additional challenges include infrastructure modernization, radiologist and technologist training, standardization of acquisition protocols, interoperability with existing imaging systems, regulatory approval of quantitative biomarkers, and the need for harmonized multicenter validation studies. These considerations indicate that technological superiority alone is insufficient to guarantee immediate universal adoption.

The international perspective adopted in this review also highlights important implications for Latin America. Healthcare systems throughout the region demonstrate substantial heterogeneity regarding access to advanced diagnostic imaging technologies. Large academic institutions and tertiary referral centers in countries such as Brazil, Mexico, Argentina, Chile, and Colombia have progressively increased participation in international collaborative research, facilitating technology transfer and scientific development. Nevertheless, equitable implementation of photon-counting CT will require continued investment in infrastructure, professional education, multidisciplinary collaboration, and regional research networks capable of generating locally relevant clinical evidence.

Several limitations of the present review should also be acknowledged. First, although a broad range of peer-reviewed publications was analyzed, the available literature remains relatively recent because clinical implementation of photon-counting CT has only begun during the past few years. Consequently, long-term outcome studies remain limited. Second, many published investigations originate from highly specialized academic institutions with access to prototype or first-generation commercial scanners, potentially limiting generalizability to routine clinical practice. Third, methodological heterogeneity among studies—including differences in acquisition protocols, reconstruction algorithms, patient populations, and evaluated clinical endpoints—complicates direct quantitative comparison across investigations. Finally, rapidly evolving hardware and software developments indicate that current evidence will likely continue expanding over the coming years.

Future research should prioritize large multicenter prospective studies evaluating patient outcomes, diagnostic accuracy, cost-effectiveness, workflow efficiency, and long-term clinical impact. Additional investigation is also needed to establish standardized quantitative imaging biomarkers, validate artificial intelligence algorithms across diverse populations, optimize acquisition protocols for different clinical indications, and determine the economic feasibility of widespread implementation within different healthcare systems. International collaboration will be fundamental to achieving these objectives and facilitating equitable access to next-generation diagnostic imaging technologies.

In summary, the evidence analyzed throughout this review consistently supports Photon-Counting Computed Tomography as a transformative innovation capable of substantially improving diagnostic imaging across multiple medical specialties. Its combination of superior detector physics, spectral imaging, quantitative biomarker generation, radiation dose optimization, and artificial intelligence integration establishes a strong technological foundation for the continued evolution of precision medicine. Although important implementation challenges remain, the current trajectory of scientific development suggests that photon-counting CT will progressively assume an increasingly prominent role in routine clinical practice, multidisciplinary diagnosis, and personalized patient care.

CONCLUSION

Photon-Counting Computed Tomography (PCCT) represents a major technological milestone in the evolution of diagnostic imaging by overcoming several intrinsic limitations of conventional energy-integrating detector computed tomography. The evidence analyzed throughout this review demonstrates that photon-counting detector technology consistently improves spatial resolution, spectral imaging capability, tissue characterization, quantitative image analysis, and artifact reduction while simultaneously enabling lower radiation exposure across a broad spectrum of clinical applications.

The reviewed literature indicates that these technological advantages extend to multiple medical specialties, including cardiovascular, oncological, neurological, pulmonary, abdominal, musculoskeletal, and pediatric imaging. Among these areas, cardiovascular imaging currently possesses the strongest clinical evidence, particularly for coronary artery evaluation, plaque characterization, and visualization of coronary stents. Likewise, oncology, neuroimaging, and

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pediatric radiology have shown considerable benefits derived from improved tissue contrast, quantitative iodine mapping, and enhanced visualization of small anatomical structures.

An additional finding of this review is the growing integration of artificial intelligence with photon-counting CT. Deep learning reconstruction, automated segmentation, radiomics, quantitative biomarker extraction, and machine learning algorithms complement the high-quality spectral information generated by photon-counting detectors, creating opportunities for more accurate, reproducible, and individualized diagnostic assessment. This convergence supports the ongoing transition from predominantly qualitative image interpretation toward objective, data-driven precision imaging.

The available evidence also highlights the importance of radiation dose optimization. Improved detector efficiency allows diagnostic-quality examinations to be obtained with lower radiation exposure while preserving or enhancing image quality. This characteristic is particularly valuable for pediatric patients, oncology follow-up, chronic diseases requiring serial imaging, and cardiovascular surveillance, where cumulative radiation exposure remains an important clinical concern.

Despite these advances, several challenges continue to influence the widespread implementation of Photon-Counting Computed Tomography. High equipment costs, infrastructure requirements, professional training, protocol standardization, regulatory considerations, interoperability, and the need for additional multicenter validation studies remain important barriers to universal adoption. Addressing these limitations will require continued collaboration among clinicians, medical physicists, engineers, researchers, healthcare institutions, and industry partners.

From an international perspective, the progressive incorporation of photon-counting CT into healthcare systems offers significant opportunities to improve diagnostic precision and patient care. Although disparities in technological availability remain evident, particularly within many low- and middle-income countries, increasing global collaboration and ongoing technological development are expected to facilitate broader implementation in the coming years. In Latin America, continued investment in academic research, infrastructure modernization, and multidisciplinary training may play a decisive role in accelerating the clinical adoption of this technology.

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