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Original Article

PHOTON-COUNTING COMPUTED TOMOGRAPHY IN CORONARY IMAGING: A SCOPING REVIEW OF CURRENT EVIDENCE

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ABSTRACT

Photon-counting computed tomography (PCCT) represents an emerging imaging technology with potential advantages for coronary artery assessment. This scoping review aimed to characterize the current body of literature on PCCT for coronary imaging and to identify existing gaps and future research priorities. A systematic scoping review was conducted in accordance with the Arksey and O'Malley framework and PRISMA guidelines. Peer-reviewed studies published in English since 2012 were retrieved from multiple electronic databases using predefined keyword combinations. Study selection and data extraction were independently performed by multiple reviewers, with discrepancies resolved through consensus.

Thirty-one studies met the inclusion criteria. Of these, 40% involved human subjects, encompassing a total of 747 participants. Early investigations conducted between 2017 and 2021 were predominantly preclinical, whereas studies published from 2022 onward demonstrated a clear transition toward clinical application. Most clinical studies focused on coronary artery disease assessment (73.1%), followed by coronary stent evaluation (15.4%), or both (11.5%). Sample sizes in clinical studies were relatively small, ranging from

3 to 197 participants (median 61.8), and primarily included patients with known or suspected coronary artery disease. The majority of publications originated from the United States and Europe, often involving multinational collaborations, while data from other regions remained limited. Most studies compared PCCT with conventional computed tomography, with few direct comparisons to alternative imaging modalities such as magnetic resonance imaging.

Overall, the literature reflects a maturing field transitioning from technical validation to early clinical implementation. However, limitations including small sample sizes, restricted patient diversity, geographic concentration, and limited multimodality comparisons persist. Addressing these gaps through large-scale, multicenter studies, standardized methodologies, and broader international collaboration will be essential to fully define the clinical role of PCCT in coronary imaging.

الملخص

يمثّل التصوير المقطعي المحوسب المعتمد على عدّ الفوتونات (PCCT) تقنية تصويرية ناشئة تحمل مزايا محتملة في تقييم الشرايين التاجية. هدفت هذه المراجعة الاستقصائية إلى توصيف الوضع الراهن للأدبيات العلمية المتعلقة باستخدام هذه التقنية في تصوير الشرايين التاجية، وتحديد الثغرات المعرفية القائمة وأولويات البحث المستقبلية. أُجريت مراجعة استقصائية منهجية وفق إطار عمل آركسي وأومالي، وبالالتزام بإرشادات البيانات المفضلة لإعداد التقارير في المراجعات المنهجية والتحليلات الشمولية (PRISMA). وقد استُرجعت الدراسات المحكمة المنشورة باللغة الإنجليزية منذ عام ٢٠١٢ من عدة قواعد بيانات إلكترونية باستخدام توليفات محددة مسبقًا من الكلمات المفتاحية. ونُفِّذت عملية اختيار الدراسات واستخلاص البيانات بصورة مستقلة من قبل عدة مراجعين، مع حلّ أي اختلافات عبر التوافق.

استوفت ٣١ دراسة معايير الاشتمال. ومن بينها، تضمنت ٤٠٪ دراسات أُجريت على البشر، شملت ما مجموعه ٧٤٧ مشاركًا. وكانت الدراسات المبكرة المنشورة بين عامي ٢٠١٧ و٢٠٢١ ذات طابع قبل سريري في الغالب، في حين أظهرت الدراسات المنشورة منذ عام ٢٠٢٢ انتقالًا واضحًا نحو التطبيق السريري. ركزت معظم الدراسات السريرية على تقييم مرض الشريان التاجي بنسبة ٧٣,١٪، تلتها دراسات تقييم الدعامات التاجية بنسبة ١٥,٤٪، أو تناولت الجانبين معًا بنسبة ١١,٥٪. وكانت أحجام العينات في الدراسات السريرية صغيرة نسبيًا، إذ تراوحت بين ٣ و١٩٧ مشاركًا (بوسيط قدره ٦١,٨)، وشملت في الغالب مرضى لديهم مرض تاجي معروف أو مشتبه به. وقد صدرت غالبية المنشورات من الولايات المتحدة وأوروبا، وغالبًا ضمن تعاونات بحثية متعددة الجنسيات، في حين

ظلت البيانات الواردة من مناطق أخرى محدودة. كما قارنت معظم الدراسات بين التصوير المقطعي المحوسب المعتمد على عدّ الفوتونات والتصوير المقطعي المحوسب التقليدي، مع قلة الدراسات التي أجرت مقارنات مباشرة مع طرائق تصوير أخرى مثل التصوير بالرنين المغناطيسي.

وبوجه عام، تعكس الأدبيات العلمية مجالًا آخذًا في النضج ينتقل تدريجيًا من مرحلة التحقق التقني إلى التطبيق السريري المبكر. ومع ذلك، لا تزال عدة قيود قائمة، من بينها صغر أحجام العينات، ومحدودية تنوع المرضى، والتركّز الجغرافي للدراسات، إضافة إلى قلة المقارنات بين طرائق التصوير المختلفة. ومن ثمّ، فإن معالجة هذه الفجوات من خلال دراسات واسعة النطاق متعددة المراكز، واعتماد منهجيات معيارية، وتوسيع نطاق التعاون الدولي ستكون خطوات أساسية لتحديد الدور السريري الكامل لهذه التقنية في تصوير الشرايين التاجية.

Keywords: Atherosclerosis Imaging, Cardiovascular, Coronary Artery Disease, Coronary Imaging, Myocardial Imaging, Photon-Counting CT, Scoping Review

1. INTRODUCTION

Coronary artery disease (CAD) remains one of the leading global causes of morbidity and mortality [1,2]. Early and accurate diagnosis is crucial for effective management, with imaging—especially computed tomography (CT)—playing a key role, which provides detailed anatomical information, enabling non-invasive visualization of coronary arteries to detect stenoses and plaque burden. Its high sensitivity and negative predictive value make CT a valuable tool in diagnosing and managing CAD [3,4].

Despite these advantages, conventional CT imaging has notable limitations. These include radiation exposure, particularly concerning in longitudinal studies, and suboptimal image quality in patients with high coronary calcium burden, limiting its accuracy in such cases [5]. Moreover, cardiac and respiratory motion can degrade image quality [6]. Thus, while conventional CT offers significant benefits in CAD imaging, carefully considering its limitations is essential in clinical decision-making.

On the contrary, photon-counting detectors in photon-counting computed tomography (PCCT) systems count individual photons and measure their energies, enabling spectral imaging with superior material differentiation compared to conventional energy-integrating detectors [7]. PCCT is particularly promising for cardiovascular imaging, excelling in detecting and quantifying coronary artery stenosis, assessing plaque composition, and identifying vulnerable plaques [8,9]. Preliminary studies have shown that PCCT outperforms conventional CT in diagnostic coronary imaging in humans [10]. Moreover, PCCT effectively eliminates iodine-based attenuation from contrast-enhanced images, enabling accurate calcium quantification with excellent correlation to the reference standard true non-contrast CT calcium score [11].

Furthermore, a key advantage of PCCT is its ability to reduce radiation doses while maintaining image quality. By using energy discrimination, PCCT achieves higher contrast-to-noise ratios at lower radiation doses, with studies reporting significant reductions without compromising image quality [12,13]. This is particularly important in coronary imaging, where minimizing radiation exposure is critical due to the need for repeated scans in some patients. Additionally, PCCT's spectral imaging capability enables material decomposition, distinguishing between tissue types and contrast agents. This feature enhances the visualization of coronary arteries, differentiating between calcified and non-calcified plaques. As a result, nearly half of the recommended downstream exams, such as functional evaluations and invasive coronary angiography, could be avoided in those patients [14].

Yet, PCCT faces several technical challenges as well as issues related to cost and availability making widespread adoption in clinical settings challenging. However, as the technology matures, significant cost reductions are anticipated [8]. For broader clinical implementation, extensive validation through large-scale clinical trials is essential. While initial studies are promising, further research is needed to establish standardized protocols, optimize imaging parameters, and confirm the clinical benefits of PCCT across diverse patient populations [3,10]. Therefore, we conducted a scoping assessment to characterize the available evidence, and research practices, and identify gaps and limitations in PCCT research on coronary imaging.

2. METHODOLOGY

As a precursor to a potential systematic review on this emerging topic, a scoping review was the most suitable study design to characterize the current literature, utilizing Arksey and O'Malley's framework and PRISMA guidelines for scoping reviews [15–17].

2.1 Study protocol

A study protocol was developed and included in this manuscript as a reference framework for executing the study. Since PROSPERO does not allow formal registration of scoping reviews, this study was not registered.

2.2 Search strategy and Eligibility criteria

The search strategy included published studies from PubMed, Web of Science, Cochrane, and EBSCO. A combination of keywords and Medical Subject Headings terms related to PCCT and coronary imaging was used to capture the full scope of the literature in this field. Studies were selected based on predefined inclusion and exclusion criteria (Table 1).

Initially, comprehensive search terms covering all aspects of PCCT and coronary imaging were used to query the selected databases, including papers published from 2012 to July 2024. The second stage of the search involved analyzing text words in titles, abstracts, keywords, and phrases. Identified Medical Subject Headings terms and phrases were then applied to search additional databases relevant to this scoping study. Subsequently, we reviewed the references of retrieved papers for further relevant studies. The search process was iterative, with researchers refining search terms and repeating steps as necessary to ensure comprehensive coverage. The search continued until no additional relevant studies were identified. “Rayyan” was used to track and manage the retrieved records.

2.2.1 Inclusion and exclusion criteria

Table 1: Shows the inclusion and exclusion criteria across different domains

Criteria	Inclusion	Exclusion	Justification
Language	Studies in English only were included.	Papers in languages other than English were excluded.	Time and financial constraints in translating literature.
Time period	All literature published from 2012 up to July 2024 was included.	Papers published beyond that time frame.	Photon-counting CT was a new research area that started around 2012, with the first scanner implemented in 2021.
Geographical area	All publications globally were covered.	No specific geographical area was excluded.	To provide a comprehensive global overview.
Publication types	All types of peer-reviewed papers were included, such as original research articles, review articles, case studies, and clinical trials.	Non-scientific literature like news articles or opinion pieces and Non-peer-reviewed papers such as conference abstracts were also excluded.	To focus on scientifically rigorous and peer-reviewed content.

Study focus	Studies mainly focused on photon-counting CT in coronary imaging were included.	Studies not focused on utilization of photon-counting CT in coronary imaging.	To maintain focus on the specific area of interest and include relevant studies only.
Subject type	Studies involving human subjects of any age, animals, or phantom models examining coronary imaging with photon-counting CT were included.	Studies dealing solely with conventional CT or other imaging methods were excluded.	To focus on the specific technology of interest.
Content availability	Articles with full text access were included.	Articles where the full text was not available were excluded.	To ensure comprehensive review of evidence.
Aspects covered	Studies covering image quality, radiation dose, and diagnostic accuracy were included.	No specific aspects were excluded.	To comprehensively review the clinical utility of photon-counting CT in coronary imaging.

2.3 Study selection

All included studies met the predefined criteria, and the data were organized using the Rayyan program. The initial screening of retrieved studies, based on titles and abstracts, was conducted independently by two reviewers. In cases of disagreement, a third reviewer resolved the conflict. Subsequently, a full-text review of the included studies was performed by three reviewers. The final number of selected studies, along with those excluded, was documented in a PRISMA flow diagram (Figure. 1).

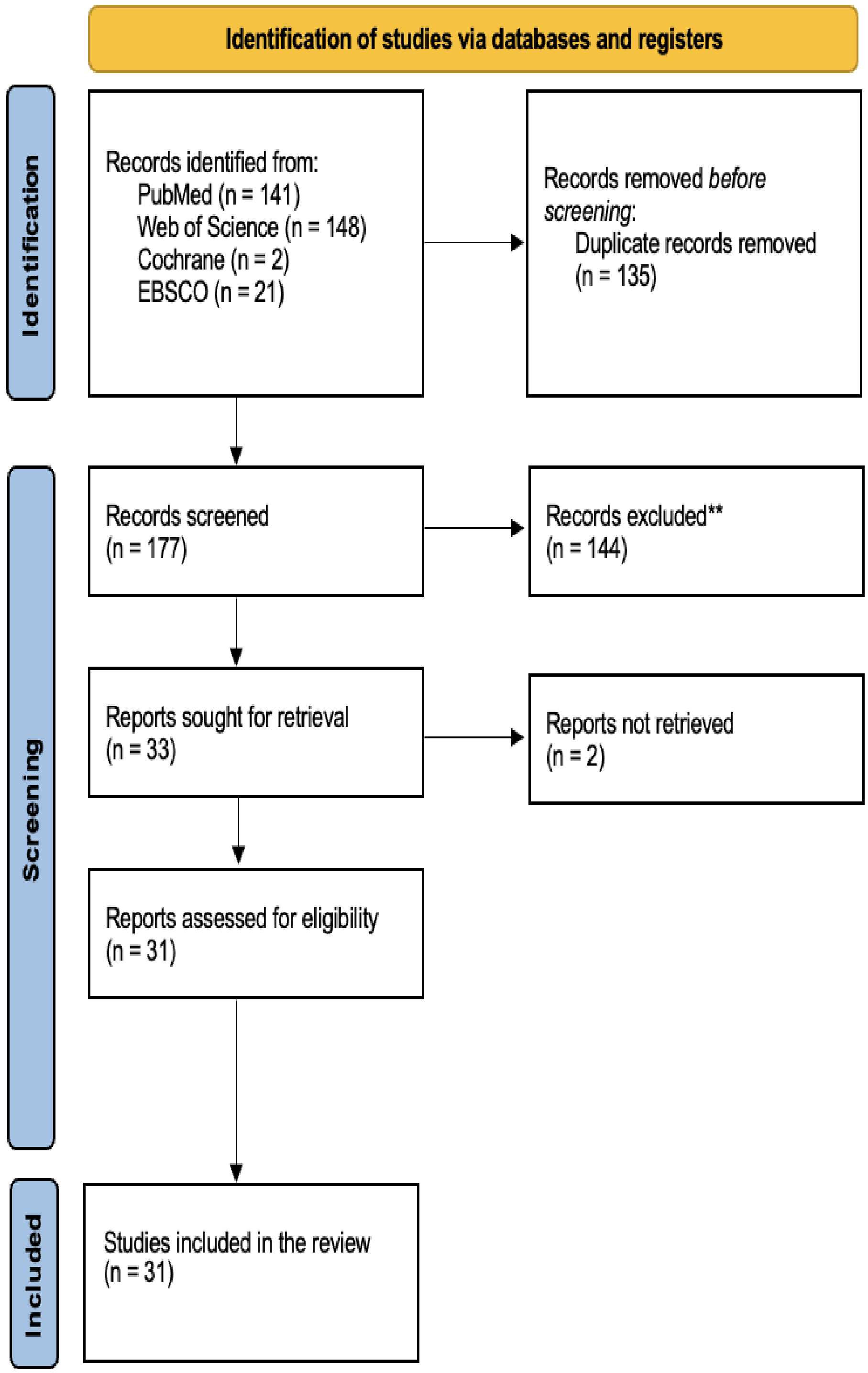

Figure 1. PRISMA flow diagram shows search results with included and excluded studies [17].

2.4 Data extraction and analysis

The research team developed a data extraction sheet based on the JBI Reviewers Manual to guide variable extraction [18]. Data extraction was conducted using "Google Sheets" to streamline workflow and enable real-time collaboration. The authors periodically reviewed the results to ensure consistency. The extracted data was under these domains:

2.4.1 Publication details

1. DOI
2. Title
3. Author(s)
4. Journal
5. Year of publication
6. Country of publication
7. Publication type

2.4.2 General study details

1. Methodological details.
2. Aim
3. Study population and sample size
4. Imaging type
5. Other compared imaging (if any)
6. Outcomes
7. Key findings related to the scoping review

3. RESULTS

This scoping review included a total of 31 studies after excluding less relevant ones based on predefined criteria. Of these, 40% of the studies involved human subjects, with a combined sample size of 747 participants (Table 2).

Table 2: Summary of Study Characteristics, Methodologies, and Imaging Comparisons in Included PCCT Coronary Imaging Studies (2017–2024)

References	Year	Country	Study Type	Methodology	Scope	Sample Size	Compared imaging Modality (if any)
[19]	2017	Multinational	Preclinical	In-vitro, Phantom	Stent	N/A	Conventional CT
[20]	2017	USA	Preclinical	In-vivo, Animal	CAD	3	Conventional CT
[21]	2019	USA	Mixed	In-vitro, Phantom; Ex-vivo, Human hearts; Humans	CAD	10	Conventional CT
[22]	2020	USA	Preclinical	In-vitro, Phantom	Stent	N/A	Conventional CT
[23]	2020	England	Preclinical	In-vitro, Phantom	CAD	N/A	Conventional CT
[24]	2021	USA	Review	Narrative review	N/A	N/A	Conventional CT
[25]	2021	USA	Preclinical	In-vitro, Phantom	Stent and CAD	N/A	Conventional CT
[26]	2021	Switzerland	Preclinical	In-vitro, Phantom	CAD	N/A	N/A
[27]	2021	England	Review	Narrative review	N/A	N/A	N/A
[28]	2022	Switzerland	Clinical	Retrospective	CAD	92	N/A

[29]	2022	Switzerland	Clinical	Prospective	CAD	30	N/A
[30]	2022	Germany	Preclinical	In-vitro, Phantom	CAD	N/A	Conventional CT
[31]	2022	Multinational	Preclinical	In-vitro, Phantom	Stent and CAD	N/A	Conventional CT
[32]	2022	USA	Mixed	In-vitro, Phantom; Humans	CAD	20	N/A
[33]	2022	USA	Clinical	Prospective	Stent	8	Conventional CT
[34]	2022	Germany	Preclinical	In-vitro, Phantom	CAD	N/A	N/A
[35]	2022	USA	Preclinical	In-vitro, Phantom	CAD	N/A	Conventional CT
[36]	2023	Switzerland	Review	Narrative review	N/A	N/A	Conventional CT
[37]	2023	Germany	Preclinical	In-vitro, Phantom	Stent	N/A	Conventional CT
[38]	2023	Switzerland	Review	Narrative review	N/A	N/A	Conventional CT
[39]	2023	USA	Clinical	Prospective	CAD	197	Conventional CT
[40]	2023	USA	Clinical	Retrospective	CAD	73	N/A
[41]	2023	France	Mixed	In-vitro, Phantom; Humans	CAD	8	Conventional CT

[42]	2023	Multinational	Preclinical	In-vitro, Phantom	CAD	N/A	N/A
[43]	2023	USA	Clinical	Prospective	CAD	68	N/A
[44]	2023	Italy	Preclinical	In-vitro, Phantom	CAD	N/A	N/A
[45]	2024	Netherlands	Mixed	In-vitro, Phantom; Humans	CAD	143	Conventional CT
[46]	2024	Ireland	Clinical	Retrospective	Stent and CAD	45	N/A
[47]	2024	Germany	Review	Narrative review	N/A	N/A	Conventional CT
[48]	2024	Switzerland	Clinical	Retrospective	CAD	53	N/A
[49]	2024	USA	Preclinical	In-vitro, Phantom	CAD	N/A	Conventional CT

3.1 Publication year

Publication activity began modestly, with minimal output in the early years, reflecting a slower phase of research engagement. From 2017 to 2021, the number of publications remained low indicating the beginning of foundational scientific work. However, starting in 2022, there was a noticeable increase in research output, signaling growing academic involvement. The most significant surge occurred in 2023, marking a peak in productivity, likely reflecting the culmination of prior research efforts. Data for 2024, which is partial and covers only up to July, suggest the final total studies will likely trend higher by the end of the year (Figure. 2).

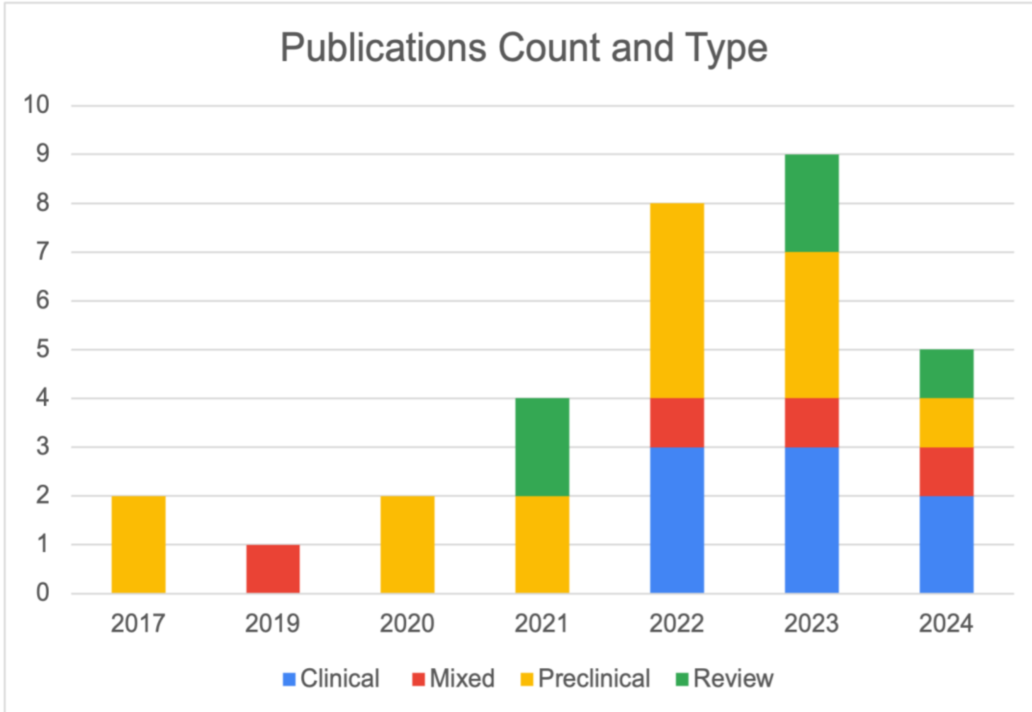

Figure 2. Bar chart shows the distribution of studies across years with a breakdown of study types.

3.2 Publication type

In terms of publication types (Figure. 2), the early years (2017–2021) are dominated by preclinical research, constituting the majority of academic output. From 2022 onward, there is a noticeable shift toward clinical research, reflecting a transition to applied studies with direct patient or clinical relevance. Review articles begin to appear around 2021, signaling a growing focus on synthesizing and analyzing existing literature. Mixed studies, combining clinical and preclinical elements, appear sporadically, primarily to compare in vivo and in vitro outcomes for specific research objectives.

3.3 Country

The distribution of publications is heavily concentrated in the United States, followed by notable contributions from Switzerland and Germany. Multinational collaborations are evident, particularly within Europe and between Europe and the United States. No studies have been published from other regions worldwide (Figure 3).

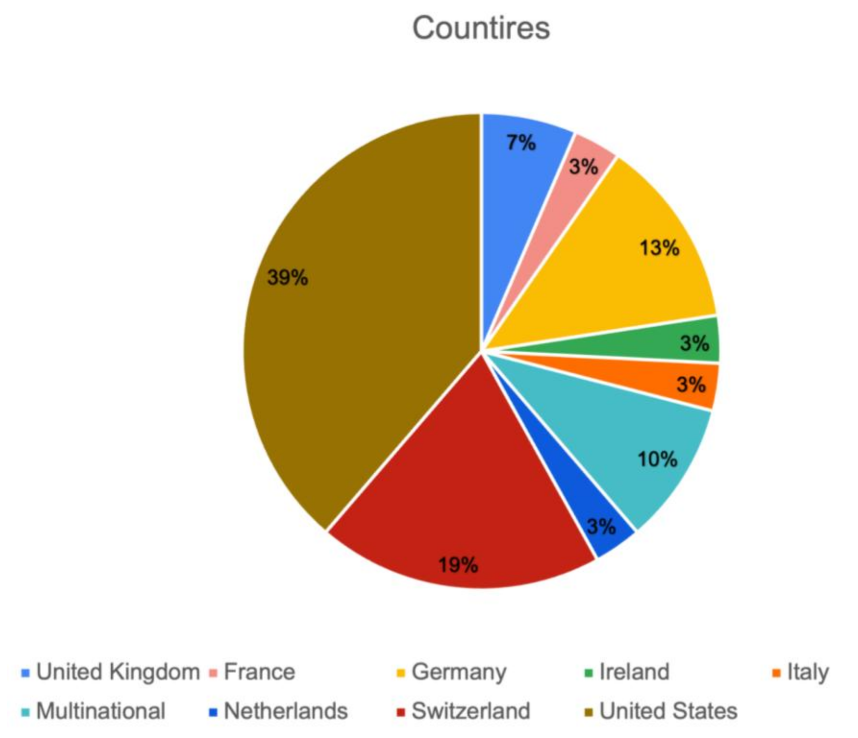

Figure 3. Pie chart shows the source countries for published studies.

3.4 Study scope

Excluding review studies, the majority of research (73.1%) focuses on CAD assessment. A smaller portion (15.4%) of the studies examine coronary stents, while 11.5% of them address both CAD and stent evaluation.

3.5 Study sample and size

Clinical studies involving human subjects have relatively small sample sizes, ranging from 3 to 197 participants, with a median of 61.8 subjects. Most studies focus on individuals with known or suspected CAD, while one study included healthy adults.

3.6 Comparison with other imaging techniques

Most experimental studies focused on comparing PCCT with conventional CT, while only one study has compared PCCT to magnetic resonance imaging.

4. DISCUSSION

4.1 Overview of Available Evidence on PCCT in Coronary Imaging

As this scoping review aims to characterize the available evidence, it tracks the progression of PCCT coronary imaging research through distinct phases, showing a clear shift from preclinical to clinical research, with reviews and mixed studies playing supportive roles. Although it seems to be still premature given the retrieved evidence on this topic, the emergence of review articles suggests a perceived maturing field among researchers with enough primary literature to warrant synthesis [7]. This progression is typical of emerging medical imaging technologies, moving from experimental validation to clinical implementation.

Geographically, the research landscape is concentrated in three main countries respectively: the United States, Switzerland, and Germany, which together account for the majority of publications. This distribution reflects the location of major research centers and technological resources allocated for this research field. Active multinational collaborations, particularly between European countries and the United States, demonstrate the field's collaborative nature. However, this geographical concentration raises concerns about the generalizability of findings across different healthcare systems and populations [3].

The research focus reveals distinct patterns, with the majority of primary studies concentrating on CAD assessment. Emerging research explores coronary stents, with some studies investigating both areas. This indicates a primary focus on CAD evaluation, with an expanding scope to include stent assessment. Clinical studies show considerable variability in sample sizes, predominantly focusing on patients with known or suspected CAD, which highlights the need for more diverse populations in future research. This variability underscores the early stage of research in the field and the need for larger, more diverse cohorts and robust methodologies to yield more reliable conclusions. Furthermore, there has been minimal investigation into PCCT's performance compared to other established imaging modalities in clinical practice.

4.2 Future Research Directions

The field's evolution from predominantly preclinical to clinical studies suggests readiness for more comprehensive validation studies. However, realizing PCCT's full potential in coronary imaging requires addressing the identified gaps through coordinated research efforts and standardized methodological approaches. Based on the identified patterns and gaps, several priority areas for future research emerge:

1. Large-scale, multicenter studies involving diverse geographical locations and healthcare settings
2. Expanded patient population studies including healthy subjects and varied demographic groups
3. Comprehensive comparative studies with multiple imaging modalities
4. Standardized reporting protocols to facilitate meaningful cross-study comparisons
5. Studies addressing currently underrepresented regions and populations

5. CONCLUSION

This scoping review examined the advancement of PCCT coronary imaging research, highlighting key trends and limitations. The field has evolved from preclinical studies to a focus on clinical research. The evidence base remains geographically concentrated in the United States and Europe, with small-sized clinical studies predominantly focusing on CAD assessment with emerging interest in stent assessment. Collaboration is evident, but contributions from other regions are lacking. To strengthen the field, future research should include larger, multicenter trials with diverse populations, expand global representation, conduct comparative studies across imaging modalities, and adopt standardized reporting protocols. These steps are crucial for broadening PCCT's clinical application in coronary imaging.

6. CONFLICT OF INTEREST

The authors declare that they have no financial, personal, or professional conflicts of interest that could have influenced the work reported in this study.

7. FUNDING

The authors also confirm that no funding or support was received that could be perceived as creating a potential conflict of interest.

DECLERATION OF GEN AI

During the preparation of this manuscript, generative artificial intelligence (AI) tools were used to assist with language editing, grammar refinement, and improving overall clarity of the text. The authors carefully reviewed and edited all AI-assisted content to ensure accuracy, integrity, and alignment with the scientific objectives of the study. The authors take full responsibility for the content of this manuscript.

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