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# Photon-Counting Computed Tomography: Experience in Musculoskeletal Imaging

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Since the emergence of the first photon-counting computed tomography (PCCT) system in late 2021, its advantages and a wide range of applications in all fields of radiology have been demonstrated. Compared to standard energy-integrating detector-CT, PCCT allows for superior geometric dose efficiency in every examination. While this aspect by itself is groundbreaking, the advantages do not stop there. PCCT facilitates an unprecedented combination of ultra-high-resolution imaging without dose penalty or field-of-view restrictions, detector-based elimination of electronic noise, and ubiquitous multi-energy spectral information. Considering the high demands of orthopedic imaging for the visualization of minuscule details while simultaneously covering large portions of skeletal and soft tissue anatomy, no subspecialty may benefit more from this novel detector technology than musculoskeletal radiology. Deeply rooted in experimental and clinical research, this review article aims to provide an introduction to the cosmos of PCCT, explain its technical basics, and highlight the most promising applications for patient care, while also mentioning current limitations that need to be overcome.

**Keywords:** Photon-counting CT; Ultra-high resolution; Musculoskeletal imaging; Multi-energy; Artifact reduction

## INTRODUCTION

Computed tomography (CT) has a long-standing pedigree in musculoskeletal imaging, providing additional information compared to conventional radiography for almost every conceivable type of pathology, such as fractures, degeneration, malignancies, and inflammatory conditions [1,2]. However, despite being mostly optimized, standard energy-integrating detector (EID) scanners fail to adequately address several current pressure points in musculoskeletal CT [3].

### Pressure Point: Radiation Dose

The added image information in CT studies (e.g., three-dimensional visualization of anatomy and quantitative image analyses) comes at the cost of an increased radiation burden. The demand for CT examinations has steadily increased in the 21st century, offsetting continuous efforts to optimize acquisition protocols for low-dose imaging. Therefore, CT scans remain the most common source of medical radiation exposure worldwide [4]. This fact is particularly concerning when considering that in a recent study, 1.3% of patients in the United States received a cumulative radiation dose of ≥ 100 mSv owing to repeated CT imaging. Of these individuals, 20% are younger than 50 years, making them more vulnerable to radiation-induced carcinogenesis [5]. In musculoskeletal imaging, many patients are young and suffer from sports-related trauma or injuries associated with an active lifestyle [6]. However, due to the inferior inherent dose efficiency, the radiation-saving potential of EID-CT—apart from lowering the absolute number of examinations—is mostly exhausted at present [7].

### Pressure Point: Spatial Resolution

As a result of ongoing technical developments such as flat-panel detector CT [8], qualitative expectations in musculoskeletal imaging have increased substantially in

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recent years. Currently, a standard-resolution examination will likely not satisfy the high demands of trauma surgeons and orthopedists regarding the delineation of trabecular bone microarchitecture [9]. Simultaneously, large portions of the anatomy are expected to be covered within the scan volume so that various differential diagnoses and injury patterns can be evaluated in a single examination [10]. With current EID-CT scanners requiring filter-based narrowing of the detector aperture to perform examinations in ultra-high-resolution (UHR) scan mode, the applicability of this technique for low-dose imaging tasks and/or larger scan volumes is considerably limited [11-13].

### Pressure Point: Metal Artifacts

Postoperative imaging remains a challenging task for radiologists in every modality owing to characteristic artifacts usually being most pronounced in the area of interest, that is, adjacent to the bone-metal interface [14]. To diagnose or rule out implant failure, screw dislocation, or periprosthetic fractures, these anatomical areas must be visualized without significant image impairment. Despite the introduction of iterative metal artifact reduction (MAR) and other post-processing features, such as virtual monoenergetic imaging (VMI) in more advanced EID-CT scanners, challenges such as beam hardening, photon starvation, and noise amplification persist [15-17].

### Pressure Point: Spectral Imaging

With the introduction of dual-energy CT, a plethora of new imaging tasks have been added to the CT portfolio. Most notably, the characteristic attenuation of different tissues at high and low kilovoltage levels can be used for material decomposition, for example, to differentiate crystal arthropathies such as gout and calcium pyrophosphate dihydrate deposition disease [18]. Post-processing of spectral data can also be employed to subtract the mineralized bone in virtual non-calcium images (VNCa), allowing for the detection of bone marrow edema (“bone bruise”) [19] or malignant bone marrow infiltration, e.g., in patients with multiple myeloma [20]. Despite improved spectral separation with newer generations of EID-CT systems, the inability to differentiate between two materials with very similar attenuation properties (e.g., blood and water) or generally within the same voxel remains a problem [21].

### Is Photon-Counting CT the Solution?

Photon-counting CT (PCCT) has been in development for the better part of the 21st century. The first clinical approval of a PCCT scanner for use in patients was issued by European authorities and the U.S. Food and Drug Administration in 2021 [22]. With the detector arguably being the most influential piece of hardware in CT imaging, the arrival of the first commercially available system using photon-counting technology had a major impact on the radiology community. While expectations for PCCT are high, the initial phases of experimental and clinical research have shown promising results in almost every aspect of image generation [23,24]. New options for image acquisition and post-processing, high geometric dose efficiency and resolution, and ubiquitous multi-energy spectral information constitute fascinating combinations for musculoskeletal imaging, allowing for substantial improvement in patient imaging.

This article intends to explain the technical basics of PCCT compared to established EID-CT systems and highlight promising use cases for musculoskeletal patient care while also considering current restrictions that need to be overcome in the future.

## Technical Background

In EID-CT, solid-state scintillators convert incoming X-ray photons into visible light before the light is transformed into electrical energy by photodiodes at the distal end of the detector. This two-step conversion process entails constructional restrictions such as the use of septa between the individual detector elements to prevent optical crosstalk. Furthermore, the cumulative signal of all incoming photons is registered in each detector element, subsequently preventing the readout of individual photon information [25]. Regarding spectral imaging, several vendor-specific concepts exist for EID-CT, including prospective (e.g., fast kV switching, dual-source, and split-filter imaging) and retrospective techniques (i.e., dual-layer or sandwich detector dual-energy CT) [26]. Although each approach possesses strengths and weaknesses, a common limitation lies in the scintillator-based two-step process required for energy integration [27].

Photon-counting detectors on the other hand are considered “energy-resolving,” relying on semiconductor materials to perform a single-step conversion process from incoming photon to electric pulse [28]. Because pulses are registered only if they exceed a predefined energy threshold, low-level electronic noise can be effectively eliminated (Fig. 1) [29]. By further increasing the

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**Fig. 1.** Standard-resolution whole-body low-dose CT scans with EID **(A)** and photon-counting detector **(B)** technology depict two osteolytic lesions in the left iliac bone (arrows) of a 69-year-old male with multiple myeloma. Note the substantially higher image noise level in EID-CT despite comparable acquisition and reconstruction settings. EID = energy-integrating detector, PCCT = photon-counting computed tomography

geometric dose efficiency, that is, the effectiveness of the detector in capturing applied radiation doses and converting them into image information, the detector cells are defined by the electric field between the common cathode and the pixelated anode, rendering the use of optical septa obsolete [30]. Although only one cadmium-telluride-based PCCT system was commercially available for clinical patient care at the time of this writing, several scanner prototypes employing different semiconductor materials, such as silicone or cadmium zinc telluride, have been used in preclinical research with promising results [31,32].

## Radiation Dose Reduction

A plethora of dose reduction concepts have been proposed for EID-CT in recent decades, such as automated tube voltage selection [33], sector- or organ-based tube current modulation [34], adaptive collimation [35], camera-based patient positioning [36], and spectral shaping via tin prefiltration [37], just to name a few. While these concepts have been integrated into a first-generation dual-source PCCT system approved for clinical imaging (Naeotom Alpha, Siemens Healthineers, Forchheim, Germany), the constructional superiority of the detector itself sets PCCT apart from EID-CT scanners in prior generations. Demonstrated for a wide range of clinical applications, PCCT allows for a considerable reduction in radiation exposure compared to EID-CT when maintaining a constant image quality [38,39] or superior image quality when matching the radiation dose [40,41]. There are several potential reasons for generating better images with lower doses, with the reduction in image noise and subsequent improvement in signal-to-noise and contrast-to-noise ratios being among the most striking. Notably, the inherent advantage of PCCT is dose-dependent, exhibiting greater benefits at lower doses [42]. This effect is particularly evident in musculoskeletal imaging, where the use of sharp convolution kernels results in an increased level of image noise [43]. By acquiring spectral data based on a hardened kilovoltage spectrum in combination with an inherent elimination of electronic noise, PCCT facilitates superior image quality, particularly in obese patients [44].

For examination of the appendicular skeleton, cone-beam CT with a specialized scanner architecture has been increasingly used in recent years [45,46]. However, for imaging of the radiation-sensitive body trunk, a gantry-based setup, such as the one used in PCCT, is still considered the standard of care [22]. Particularly for scans of the axial skeleton and large joints, the advent of PCCT offers a compelling combination of advantages [47,48].

## Spatial Resolution Improvement

The dose reduction potential of PCCT is most pronounced when scanning in UHR mode, which is used extensively in musculoskeletal imaging [11,49,50]. With conventional EID-CT, positioning a comb or grid filter in front of the detector array is necessary to narrow the pixel aperture for UHR scans [51]. While this method effectively improves spatial resolution, the setup has two major drawbacks. First, X-ray photons that have already passed through the patient do not contribute to image generation. While only 54% of X-ray quanta pass through a comb filter, the relative number is even smaller in grid-filter-based EID-CT (34%) [52]. Owing to their different builds, PCCT detectors do not rely on comb or grid filters to generate UHR data (Fig. 2). Instead, independence from interpixel septa allows for the design of smaller pixels, which can be read out separately in UHR mode or with 2 x 2 pixel binning for standard-resolution imaging [3]. Second, the maximum scan volume is significantly limited in UHR-EID-CT; hence, only smaller anatomical regions can be examined with a high spatial resolution. Whereas the detector collimation for UHR mode in EID-CT typically ranges between 0.6–16 x 0.6 mm [52], the collimation for UHR-PCCT is 120 x 0.2 mm, constituting a substantial increase in collimation width [53].

Notably, the thinnest achievable slice thickness on UHR-EID-CT is matched by standard-resolution PCCT [41]. While a higher spatial resolution in z-direction may be particularly advantageous in hand or foot imaging owing to the minuscule size of the anatomical components and their intercompartmental dependency to provide biomechanical stability, larger joints, such as the shoulder or hip, also benefit from PCCT examinations in UHR mode with a minimum slice thickness of 0.2 mm [12,47,50]. Allowing for a larger image matrix of $1024^2$ pixels with the current configuration of the dual-source scanner, the PCCT scanner automatically selects an appropriate matrix size depending on the chosen field of view and convolution kernel [54-56].

Compared to standard PCCT imaging, UHR-PCCT displayed a significant reduction in image noise owing to the smaller pixel size in the fan direction (Fig. 3). Assuming an identical radiation dose, a scan mode with smaller detector pixels will allow for better spatial resolution, albeit at the cost of higher image noise, when the data are reconstructed with the maximum resolution. However, when the data from both scan modes are reconstructed with the same resolution (below the limit of each mode), the UHR noise level is lower than that of the standard resolution mode. This so-called "small pixel effect" can be used either for dose reduction or higher spatial resolution, depending on the selected

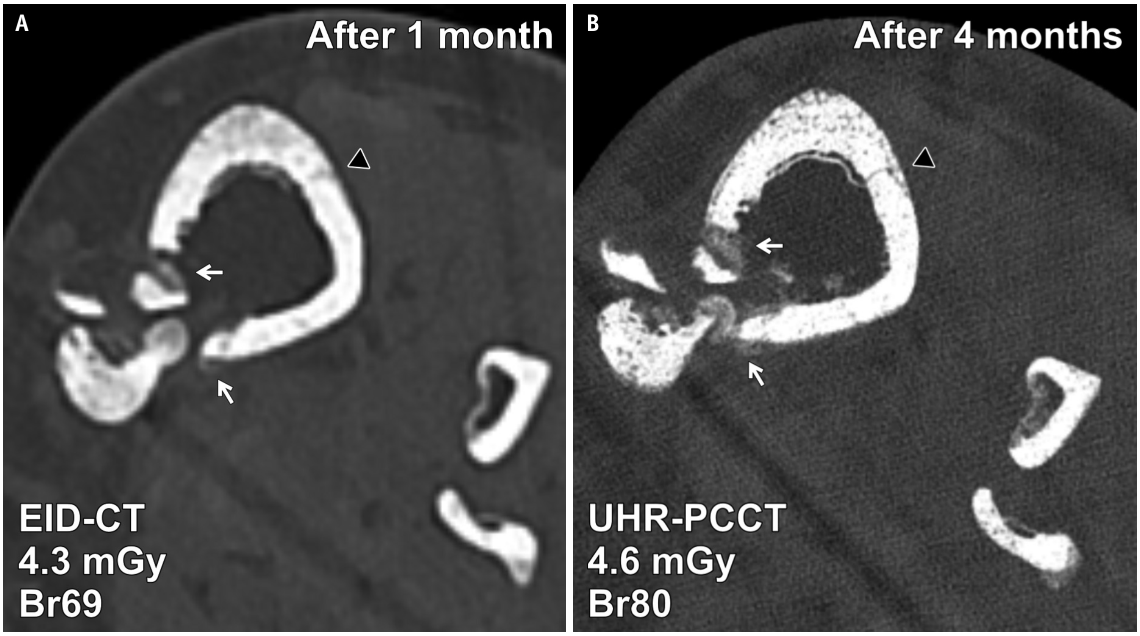

**Fig. 2.** A 29-year-old male was involved in a motorcycle accident, suffering a displaced multi-fragment injury of his left lower leg. **A, B:** UHR-PCCT at 140 kVp **(B)** allows for superior discrimination of bone microarchitecture (arrowheads) and callus formation over time (arrows) compared with standard-resolution EID-CT at 150 kVp **(A)**. Notably, UHR mode was not available for the initial EID-CT scan owing to the size of the requested scan volume. UHR = ultra-high-resolution, PCCT = photon-counting computed tomography, EID = energy-integrating detector

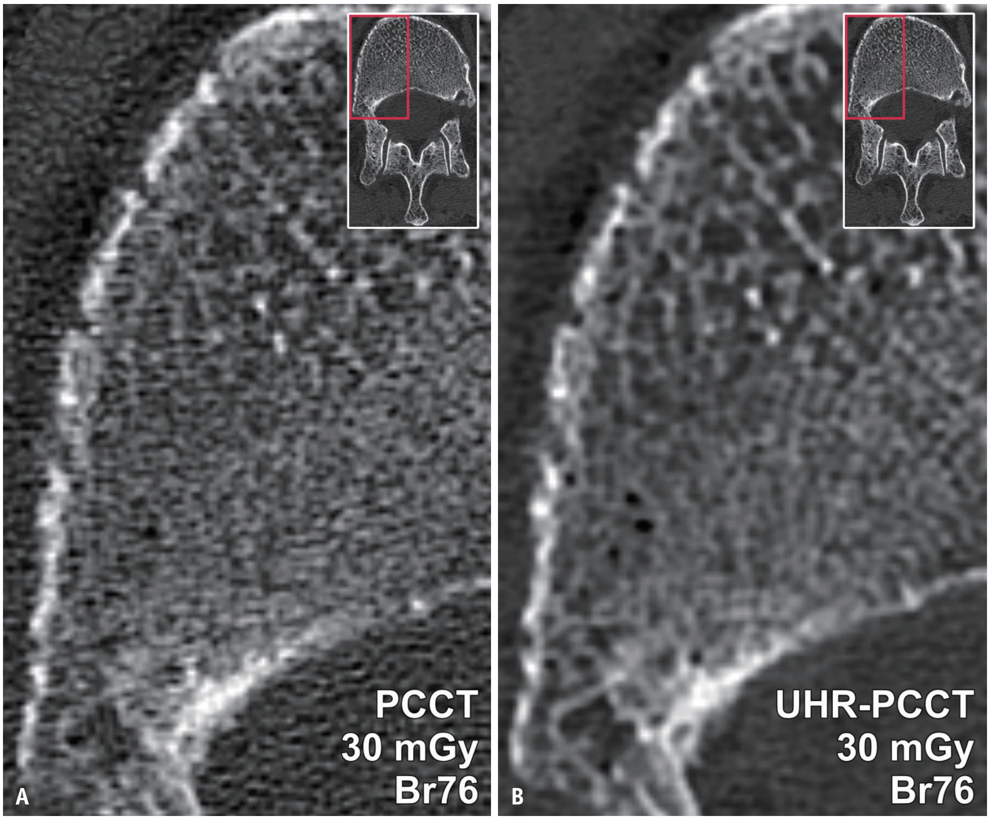

**Fig. 3.** Magnified side-by-side comparison of the trabecular microarchitecture in the third lumbar vertebra of a cadaveric specimen. **A, B:** Standard-resolution **(A)** and UHR-PCCT data **(B)** acquired at 140 kVp were reconstructed with the sharpest convolution kernel available for both scan modes. The small pixel effect facilitates a considerable noise reduction in UHR images, which can be used to lower the radiation dose. UHR = ultra-high-resolution, PCCT = photon-counting computed tomography

convolution kernel [57-59]. However, several drawbacks of UHR-PCCT must be acknowledged. First, the maximum tube output is reduced to prevent anode damage because of the small focal spot [3]. Second, the raw data file sizes increase significantly when scanning in UHR mode [60]. Third, reconstruction times are longer, potentially affecting clinical workflow and patient throughput [61].

## Metal Artifact Reduction

Irrespective of detector design, most modern CT scanners employ similar principles to reduce metal artifacts. One widely established technique is to increase the tube voltage, for example, from 100 to 140 kVp. The resulting artifact reduction can be amplified by further hardening of the X-ray spectrum through additional prefiltration [39]. Depending on the system manufacturer, either a pre-patient silver or tin filter is utilized for this purpose, absorbing low-energy photons before they pass through the patient and contribute to the radiation dose. Regarding filter/voltage combinations, smaller modifications have been implemented from one scanner generation to another; in third-generation dual-source EID-CT, spectral shaping relies on a 0.6 mm tin filter for examinations up to 150 kVp [62]. In contrast, the current dual-source PCCT system employs a 0.4 mm tin filter for beam hardening at either 100 or 140 kVp [63]. Although prefiltration allows reliable artifact reduction, this setup also results in a perceptible loss of image contrast [64]. Therefore, artificially hardened spectra should not be used in combination with iodine contrast agents; otherwise, this technique has no major restrictions.

A second effective approach to reducing metal artifacts is the use of dedicated postprocessing algorithms, which yield good results in the latest generation of EID-CT scanners [62]. Despite not being optimized for photon-counting data, iterative MAR has shown promise in PCCT for various types of implants, irrespective of the selected acquisition protocol [65,66]. However, with the current software, MAR postprocessing cannot be combined with a spatial frequency higher than 7.3 line pairs per centimeter at 50%

of the modulation transfer function (Br56 kernel; Siemens Healthineers) [14], which is far from the image sharpness expected from UHR imaging.

Another promising technique for reducing the extent of hyperdense and hypodense artifacts in postoperative assessments following osteosynthesis is VMI. Based on the acquisition of dual- or polyenergetic data, specific postprocessing allows for the reconstruction of separate image stacks with information from a single portion of the energy spectrum [67]. Because every PCCT scan (even when acquired with tin prefiltration) allows for spectral postprocessing, VMI is now applicable to an even wider range of imaging tasks, for example, Sn 140 kVp acquisitions. As previously shown for a multitude of implants and metallic devices in EID-CT, the use of high-keV levels is especially effective for artifact reduction [16]. However, similar to iterative MAR, VMI cannot be combined with ultrasharp reconstruction kernels with a spatial frequency above 16.5 line pairs per cm at 50% of the modulation transfer function [14]. Although both VMI and MAR can be applied to a dataset synergistically, restricted image sharpness limits the number of use cases for this powerful artifact reduction tool (Fig. 4) [66].

## Multi-Energy and Spectral Imaging Improvement

Numerous dual-energy CT systems based on conventional EID technology are available from various vendors. These scanners typically derive spectral information from individual datasets obtained from two spectra. For example, in dual-source scanners, two X-ray tubes operate simultaneously, one at a low voltage (usually 70–100 kVp) and the other at a high voltage (140 kVp or Sn 150 kVp), to achieve sufficient separation of the X-ray spectra, thereby enhancing the accuracy of dual-energy postprocessing [68]. However, the dual-source setup also limits the dual-energy field of view because the spectral information is only available within the overlap of both X-ray beams [69]. Furthermore, this scan option must be selected before the examination commences. In contrast, one key strength of PCCT is its ability to generate polyenergetic data in every scan; therefore, the acquisition of spectral image information can now be considered a part of the clinical routine [70]. While VMI reconstructions are subject to personal preferences and modifiable for specific needs, their main application in musculoskeletal imaging lies arguably in the amplification of contrast (low keV), and the reduction of noise and

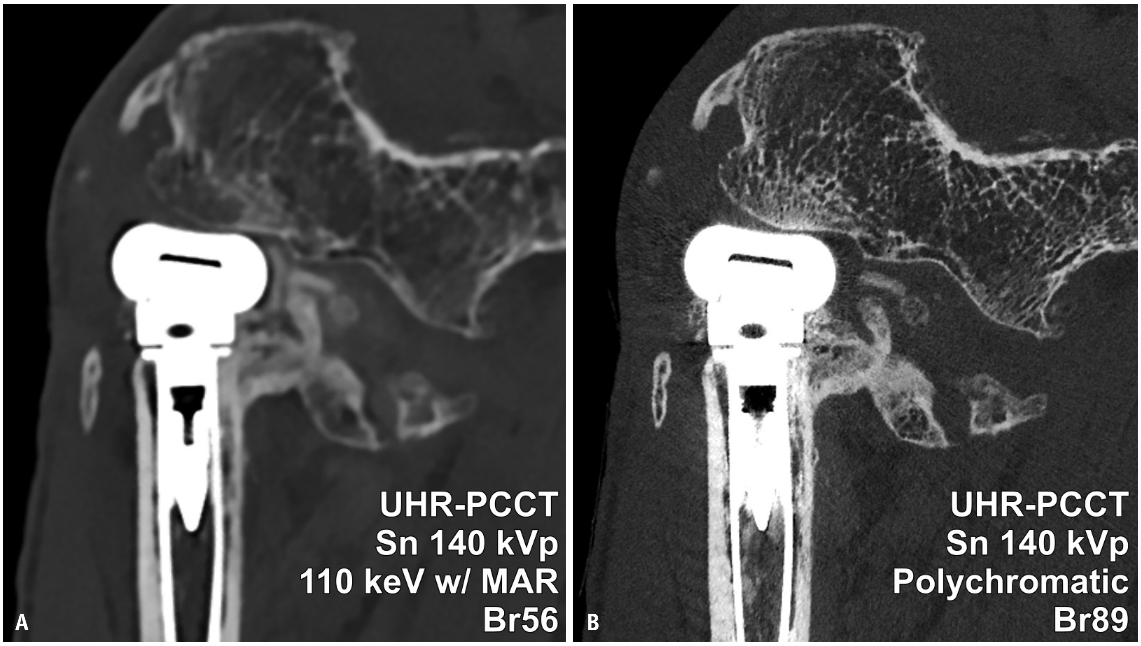

**Fig. 4.** UHR-PCCT elbow scan with tin prefiltration at 140 kVp in a 66-year-old female after radial head replacement. **A, B:** Whereas the combination of virtual monoenergetic imaging at 110 keV and MAR postprocessing allows for superior artifact reduction **(A)**, the limited reconstruction sharpness hampers diagnostic assessability. Meanwhile, the use of an ultra-sharp bone kernel for polychromatic data facilitates better visualization of osseous tissue albeit at the cost of increased artifact intensity at the bone-metal interface **(B)**. UHR = ultra-high-resolution, PCCT = photon-counting computed tomography, MAR = metal artifact reduction

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artifacts (high keV). The acquisition of spectral data at a relatively high tube voltage of 120 or 140 kVp constitutes another advantage of PCCT over EID-CT. Because the latter relies on acquisition at higher and lower tube voltages, image quality and spectral postprocessing may be limited to a certain degree in obese patients [71]. In contrast, the harder spectrum in PCCT contributes to a lower noise level and artifact intensity, both of which potentially aid material decomposition.

Multiple use cases of spectral CT in musculoskeletal radiology have been discussed since the first EID-based dual-energy system was introduced; however, none have been considered more promising than functional bone marrow imaging [72]. Because a VNCa option will soon become available for PCCT, the option to analyze bone bruise in UHR examinations may change the assessment of traumatic injuries in routine clinical practice. With the only commercially available PCCT scanner being a dual-source system, there is also the potential to operate both tubes with different X-ray spectra, which may provide additional benefits regarding spectral separation over a wide kVp range. Currently, the full range of spectral postprocessing options in PCCT is difficult to predict, and there may be use cases other than those already established for EID-CT when all features are made accessible. One promising application is improved subtraction of contrast agents injected into the articular cavity for direct CT arthrography [73]. By combining soft tissue information with a higher spatial resolution than that in EID-CT, short scan times, and the option to generate unimpaired 3D models of fracture patterns for preoperative planning, UHR-PCCT arthrography may have the potential to become the new gold standard for joint imaging (Fig. 5) [43].

Regarding oncological musculoskeletal imaging, the advantages of PCCT-VNCa for bone bruise mapping may also aid in the diagnosis of malignant bone marrow infiltration, such as in patients with multiple myeloma [70,74,75]. Another novel use case for differentiating solid tumors may lie in the separation of different contrast agents, which is neither reliably feasible on grayscale images nor in dual-energy EID-CT [76]. Whether multi- and single-material maps derived from polycontrast PCCT data are truly capable of revolutionizing diagnostic assessment in musculoskeletal oncology remains to be seen, though.

## Current Technical Limitations and Outlook

Since the introduction of the first clinical PCCT scanner in 2021, numerous studies have praised its improved image quality, potential for radiation dose reduction, and superior contrast attenuation [9,11,39,40]. The latter has had a significant impact on cardiovascular imaging, resulting in novel scan protocols with considerably lower contrast agent volumes [77]. Meanwhile, musculoskeletal radiologists are anxiously awaiting their next PCCT-related "breakthrough moment," which should come with the emergence of new spectral postprocessing features, such as bone marrow imaging. Thus, the first major articles on functional PCCT imaging are likely to be published in 2024. These studies will hopefully investigate the clinical impact of PCCT on treatment decision-making in musculoskeletal conditions, an aspect that is severely underrepresented in the photon-counting literature.

As the potential for an even higher spatial resolution remains unclear, one may expect that the current UHR

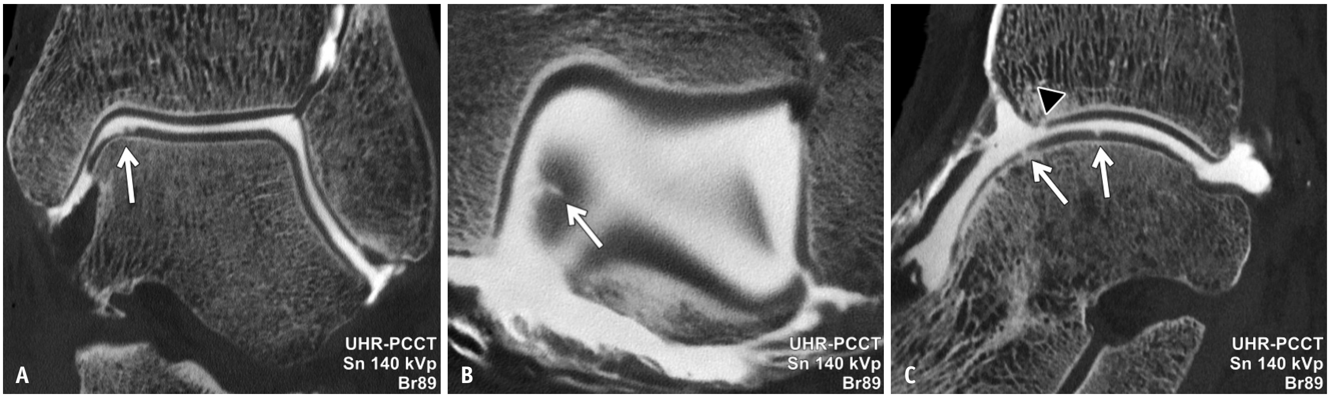

**Fig. 5.** UHR-PCCT arthrography of the left ankle of a 58-year-old female. **A-C:** While the articular injection of iodine-based contrast agent aids the depiction of minute cartilage injuries of the talus bone (arrows) and distal tibia (arrowhead), the virtual subtraction of contrast material may be helpful when generating three-dimensional models for preoperative planning. UHR = ultra-high-resolution, PCCT = photon-counting computed tomography

mode could become the standard in the future, assuming that data connectivity and processing time restrictions are overcome. In musculoskeletal imaging, this development would certainly be welcomed with open arms. Although reconstruction sharpness remains a concern for MAR and VMI, especially in small bone and joint imaging [14,66], this problem may also be solved with future software updates. Whether PCCT scanners from other vendors will receive clinical approval in the near future remains a subject of speculation. However, one may assume that the parallel availability of multiple photon-counting concepts would not be disadvantageous to radiologists or patients. Ongoing preclinical studies have explored the use of alternative contrast agents (e.g., bismuth); however, the actual clinical benefits are not yet foreseeable [78,79].

Despite these limitations, the technological leap through PCCT has been substantial, paralleled only by the increased demand placed on users. Not only do technologists need to acclimate to the new hardware and myriad postprocessing options, but radiologists must also engage with the examination protocols. Photon-counting scanners permit an almost infinite number of modifications to precisely tailor the scan and reconstruction settings to individual requirements of image quality and radiation dosage [80]. Particularly in musculoskeletal radiology, where clinical colleagues are frequently involved in the reading process, close collaboration between trauma surgeons and orthopedists is essential to ensure optimal imaging results. However, the challenge posed by the system extends beyond image acquisition, as it also encompasses the reconstruction and archiving of vast amounts of data, necessitating deliberate and conscious engagement.

## Summary

PCCT represents a pivotal advancement for radiology in general, and for musculoskeletal radiology in particular. Offering crucial advantages in terms of spatial resolution and dose efficiency, almost every imaging task benefits from using a photon-counting detector. With a range of new postprocessing options becoming accessible in the near future, PCCT scanners are poised to revolutionize functional imaging and provide ubiquitous spectral information, even during UHR examinations. Overall, the trajectory is clear; conventional EID-based CT systems are gradually making way for a new detector technology to take center stage.

### Conflicts of Interest

Jan-Peter Grunz has received speaker honoraria from Siemens Healthineers outside of the presented work within the last three years. Henner Huflage has declared no conflicts of interest.

### Author Contributions

Funding acquisition: Jan-Peter Grunz. Visualization: all authors. Writing—original draft: all authors. Writing—review & editing: all authors.

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## REFERENCES

1. Ibad HA, de Cesar Netto C, Shakoor D, Sisniega A, Liu SZ, Siewerdsen JH, et al. Computed tomography: state-of-the-art advancements in musculoskeletal imaging. *Invest Radiol* 2023;58:99-110
2. Demehri S, Baffour FI, Klein JG, Ghotbi E, Ibad HA, Moradi K, et al. Musculoskeletal CT imaging: state-of-the-art advancements and future directions. *Radiology* 2023;308:e230344
3. Lell M, Kachelrieß M. Computed tomography 2.0: new detector technology, AI, and other developments. *Invest Radiol* 2023;58:587-601
4. Martin CJ, Harrison JD, Rehani MM. Effective dose from radiation exposure in medicine: past, present, and future. *Phys Med* 2020;79:87-92
5. Rehani MM, Yang K, Melick ER, Heil J, Šalát D, Sensakovic WF, et al. Patients undergoing recurrent CT scans: assessing the magnitude. *Eur Radiol* 2020;30:1828-1836
6. Browne GJ, Barnett PLJ. Common sports-related musculoskeletal injuries presenting to the emergency department. *J Paediatr Child Health* 2016;52:231-236
7. Grunz JP, Petritsch B, Luetkens KS, Kunz AS, Lennartz S, Ergün S, et al. Ultra-low-dose photon-counting CT imaging of the paranasal sinus with tin prefiltration: how low can we go? *Invest Radiol* 2022;57:728-733

8. Grunz JP, Jordan MC, Schmitt R, Luetkens KS, Huflage H, Meffert RH, et al. Gantry-free high-resolution cone-beam CT: efficacy for distal radius and scaphoid fracture detection and characterization. *Acad Radiol* 2023;30:1358-1366
9. Conrads N, Grunz JP, Huflage H, Luetkens KS, Feldle P, Pennig L, et al. Ultrahigh-resolution computed tomography of the cervical spine without dose penalty employing a cadmium-telluride photon-counting detector. *Eur J Radiol* 2023;160:110718
10. Esquivel A, Ferrero A, Mileto A, Baffour F, Horst K, Rajiah PS, et al. Photon-counting detector CT: key points radiologists should know. *Korean J Radiol* 2022;23:854-865
11. Rajendran K, Baffour F, Powell G, Glazebrook K, Thorne J, Larson N, et al. Improved visualization of the wrist at lower radiation dose with photon-counting-detector CT. *Skeletal Radiol* 2023;52:23-29
12. Patzer TS, Kunz AS, Huflage H, Luetkens KS, Conrads N, Gruschwitz P, et al. Quantitative and qualitative image quality assessment in shoulder examinations with a first-generation photon-counting detector CT. *Sci Rep* 2023;13:8226
13. Pourmorteza A, Symons R, Henning A, Ulzheimer S, Bluemke DA. Dose efficiency of quarter-millimeter photon-counting computed tomography: first-in-human results. *Invest Radiol* 2018;53:365-372
14. Patzer TS, Grunz JP, Huflage H, Hennes JL, Pannenbecker P, Gruschwitz P, et al. Ultra-high resolution photon-counting CT with tin prefiltration for bone-metal interface visualization. *Eur J Radiol* 2024;170:111209
15. Große Hokamp N, Neuhaus V, Abdullayev N, Laukamp K, Lennartz S, Mpotsaris A, et al. Reduction of artifacts caused by orthopedic hardware in the spine in spectral detector CT examinations using virtual monoenergetic image reconstructions and metal-artifact-reduction algorithms. *Skeletal Radiol* 2018;47:195-201
16. Schreck J, Laukamp KR, Niehoff JH, Michael AE, Boriesosdick J, Wöltjen MM, et al. Metal artifact reduction in patients with total hip replacements: evaluation of clinical photon counting CT using virtual monoenergetic images. *Eur Radiol* 2023;33:9286-9295
17. Leng S, Bruesewitz M, Tao S, Rajendran K, Halaweish AF, Campeau NG, et al. Photon-counting detector CT: system design and clinical applications of an emerging technology. *Radiographics* 2019;39:729-743
18. Kravchenko D, Karakostas P, Kuetting D, Meyer C, Brossart P, Behning C, et al. The role of dual energy computed tomography in the differentiation of acute gout flares and acute calcium pyrophosphate crystal arthritis. *Clin Rheumatol* 2022;41:223-233
19. Petritsch B, Kosmala A, Weng AM, Krauss B, Heidemeier A, Wagner R, et al. Vertebral compression fractures: third-generation dual-energy CT for detection of bone marrow edema at visual and quantitative analyses. *Radiology* 2017;284:161-168
20. Kosmala A, Weng AM, Heidemeier A, Krauss B, Knop S, Bley TA, et al. Multiple myeloma and dual-energy CT: diagnostic accuracy of virtual noncalcium technique for detection of bone marrow infiltration of the spine and pelvis. *Radiology* 2018;286:205-213
21. Greffier J, Villani N, Defez D, Dabli D, Si-Mohamed S. Spectral CT imaging: technical principles of dual-energy CT and multi-energy photon-counting CT. *Diagn Interv Imaging* 2023;104:167-177
22. Baffour FI, Glazebrook KN, Ferrero A, Leng S, McCollough CH, Fletcher JG, et al. Photon-counting detector CT for musculoskeletal imaging: a clinical perspective. *AJR Am J Roentgenol* 2023;220:551-560
23. McCollough CH, Rajendran K, Baffour FI, Diehn FE, Ferrero A, Glazebrook KN, et al. Clinical applications of photon counting detector CT. *Eur Radiol* 2023;33:5309-5320
24. Gillet R, Boubaker F, Hossu G, Thay A, Gillet P, Blum A, et al. Computed tomography bone imaging: pushing the boundaries in clinical practice. *Semin Musculoskelet Radiol* 2023;27:397-410
25. Flohr T, Petersilka M, Henning A, Ulzheimer S, Ferda J, Schmidt B. Photon-counting CT review. *Phys Med* 2020;79:126-136
26. McCollough CH, Boedeker K, Cody D, Duan X, Flohr T, Halliburton SS, et al. Principles and applications of multienergy CT: report of AAPM task group 291. *Med Phys* 2020;47:e881-e912
27. McCollough CH, Rajendran K, Leng S, Yu L, Fletcher JG, Stierstorfer K, et al. The technical development of photon-counting detector CT. *Eur Radiol* 2023;33:5321-5330
28. Willemink MJ, Persson M, Pourmorteza A, Pelc NJ, Fleischmann D. Photon-counting CT: technical principles and clinical prospects. *Radiology* 2018;289:293-312
29. Sartoretti T, Wildberger JE, Flohr T, Alkadhi H. Photon-counting detector CT: early clinical experience review. *Br J Radiol* 2023;96:20220544
30. Gomes MJ, Jaseemudheen MM. Photon-counting detectors in computed tomography: a review. *J Health Allied Sci NU* 2023;13:147-152
31. Salyapongse AM, Rose SD, Pickhardt PJ, Lubner MG, Toia GV, Bujila R, et al. CT number accuracy and association with object size: a phantom study comparing energy-integrating detector CT and deep silicon photon-counting detector CT. *AJR Am J Roentgenol* 2023;221:539-547
32. Byun J, Kim Y, Seo J, Kim E, Kim K, Jo A, et al. Development and evaluation of photon-counting $\mathrm{Cd}_{0.875}\mathrm{Zn}_{0.125}\mathrm{Te}_{0.98}\mathrm{Se}_{0.02}$ detector for measuring bone mineral density. *Phys Eng Sci Med* 2023;46:245-253
33. Spearman JV, Schoepf UJ, Rottenkolber M, Driesser I, Canstein C, Thierfelder KM, et al. Effect of automated attenuation-based tube voltage selection on radiation dose at CT: an observational study on a global scale. *Radiology* 2016;279:167-174
34. Markart S, Fischer TS, Wildermuth S, Dietrich TJ, Alkadhi H, Leschka S, et al. Organ-based tube current modulation and bismuth eye shielding in pediatric head computed tomography. *Pediatr Radiol* 2022;52:2584-2594

35. Deak PD, Langner O, Lell M, Kalender WA. Effects of adaptive section collimation on patient radiation dose in multisection spiral CT. *Radiology* 2009;252:140-147
36. Manava P, Galster M, Ammon J, Singer J, Lell MM, Rieger V. Optimized camera-based patient positioning in CT: impact on radiation exposure. *Invest Radiol* 2023;58:126-130
37. Grunz JP, Halt D, Schüle S, Beer M, Hackenbroch C. Thermoluminescence dosimetry in abdominal CT for urinary stone detection: effective radiation dose reduction with tin prefiltration at 100 kVp. *Invest Radiol* 2023;58:231-238
38. Jungblut L, Euler A, von Spiczak J, Sartoretti T, Mergen V, Englmaier V, et al. Potential of photon-counting detector CT for radiation dose reduction for the assessment of interstitial lung disease in patients with systemic sclerosis. *Invest Radiol* 2022;57:773-779
39. Marth AA, Marcus RP, Feuerriegel GC, Nanz D, Sutter R. Photon-counting detector CT versus energy-integrating detector CT of the lumbar spine: comparison of radiation dose and image quality. *AJR Am J Roentgenol* 2024;222:e2329950
40. Bette SJ, Braun FM, Haerting M, Decker JA, Luitjens JH, Scheurig-Muenkler C, et al. Visualization of bone details in a novel photon-counting dual-source CT scanner-comparison with energy-integrating CT. *Eur Radiol* 2022;32:2930-2936
41. Grunz JP, Huflage H, Heidenreich JF, Ergün S, Petersilka M, Allmendinger T, et al. Image quality assessment for clinical cadmium telluride-based photon-counting computed tomography detector in cadaveric wrist imaging. *Invest Radiol* 2021;56:785-790
42. Tortora M, Gemini L, D'Iglio I, Ugga L, Spadarella G, Cuocolo R. Spectral photon-counting computed tomography: a review on technical principles and clinical applications. *J Imaging* 2022;8:112
43. Luetkens KS, Grunz JP, Kunz AS, Huflage H, Weißenberger M, Hartung V, et al. Ultra-high-resolution photon-counting detector CT arthrography of the ankle: a feasibility study. *Diagnostics (Basel)* 2023;13:2201
44. Liu LP, Shapira N, Chen AA, Shinohara RT, Sahbaee P, Schnall M, et al. First-generation clinical dual-source photon-counting CT: ultra-low-dose quantitative spectral imaging. *Eur Radiol* 2022;32:8579-8587
45. Carrino JA, Al Muhit A, Zbijewski W, Thawait GK, Stayman JW, Packard N, et al. Dedicated cone-beam CT system for extremity imaging. *Radiology* 2014;270:816-824
46. Kunz AS, Schmalzl J, Huflage H, Luetkens KS, Patzer TS, Kuhl PJ, et al. Twin robotic gantry-free cone-beam CT in acute elbow trauma. *Radiology* 2023;306:e221200
47. Marcus RP, Nagy DA, Feuerriegel GC, Anhaus J, Nanz D, Sutter R. Photon-counting detector CT with denoising for imaging of the osseous pelvis at low radiation doses: a phantom study. *AJR Am J Roentgenol* 2024;222:e2329765
48. Rau A, Straehle J, Stein T, Diallo T, Rau S, Faby S, et al. Photon-counting computed tomography (PC-CT) of the spine: impact on diagnostic confidence and radiation dose. *Eur Radiol* 2023;33:5578-5586
49. Sonnow L, Salimova N, Behrendt L, Wacker FK, Örgel M, Plagge J, et al. Photon-counting CT of elbow joint fractures: image quality in a simulated post-trauma setting with off-center positioning. *Eur Radiol Exp* 2023;7:15
50. Baffour FI, Rajendran K, Glazebrook KN, Thorne JE, Larson NB, Leng S, et al. Ultra-high-resolution imaging of the shoulder and pelvis using photon-counting-detector CT: a feasibility study in patients. *Eur Radiol* 2022;32:7079-7086
51. Meyer M, Haubenreisser H, Raupach R, Schmidt B, Lietzmann F, Leidecker C, et al. Initial results of a new generation dual source CT system using only an in-plane comb filter for ultra-high resolution temporal bone imaging. *Eur Radiol* 2015;25:178-185
52. Flohr TG, Stierstorfer K, Süss C, Schmidt B, Primak AN, McCollough CH. Novel ultrahigh resolution data acquisition and image reconstruction for multi-detector row CT. *Med Phys* 2007;34:1712-1723
53. Rajendran K, Petersilka M, Henning A, Shanblatt E, Marsh J Jr, Thorne J, et al. Full field-of-view, high-resolution, photon-counting detector CT: technical assessment and initial patient experience. *Phys Med Biol* 2021;66:205019
54. Morita Y, Yamashiro T, Tsuchiya N, Tsubakimoto M, Murayama S. Automatic bronchial segmentation on ultra-HRCT scans: advantage of the 1024-matrix size with 0.25-mm slice thickness reconstruction. *Jpn J Radiol* 2020;38:953-959
55. Euler A, Martini K, Baessler B, Eberhard M, Schoeck F, Alkadhi H, et al. 1024-pixel image matrix for chest CT–impact on image quality of bronchial structures in phantoms and patients. *PLoS One* 2020;15:e0234644
56. Tsubamoto M, Hata A, Yanagawa M, Honda O, Miyata T, Yoshida Y, et al. Ultra high-resolution computed tomography with 1024-matrix: comparison with 512-matrix for the evaluation of pulmonary nodules. *Eur J Radiol* 2020;128:109033
57. Klein L, Dorn S, Amato C, Heinze S, Uhrig M, Schlemmer HP, et al. Effects of detector sampling on noise reduction in clinical photon-counting whole-body computed tomography. *Invest Radiol* 2020;55:111-119
58. Huflage H, Hendel R, Kunz AS, Ergün S, Afat S, Petri N, et al. Investigating the small pixel effect in ultra-high resolution photon-counting CT of the lung. *Invest Radiol* 2024;59:293-297
59. Fix Martinez M, Klein L, Maier J, Rotkopf LT, Schlemmer HP, Schönberg SO, et al. Potential radiation dose reduction in clinical photon-counting CT by the small pixel effect: ultra-high resolution (UHR) acquisitions reconstructed to standard resolution. *Eur Radiol* 2023 Dec 22 [Epub]. https://doi.org/10.1007/s00330-023-10499-1
60. Gruschwitz P, Hartung V, Ergün S, Peter D, Lichthardt S, Huflage H, et al. Comparison of ultrahigh and standard resolution photon-counting CT angiography of the femoral arteries in a continuously perfused in vitro model. *Eur Radiol Exp* 2023;7:83
61. Flohr T, Schmidt B. Technical basics and clinical benefits of photon-counting CT. *Invest Radiol* 2023;58:441-450
62. Hackenbroch C, Schüle S, Halt D, Zengerle L, Beer M.

Metal artifact reduction with tin prefiltration in computed tomography: a cadaver study for comparison with other novel techniques. *Invest Radiol* 2022;57:194-203
63. Patzer TS, Kunz AS, Huflage H, Luetkens KS, Conrads N, Pannenbecker P, et al. Rotational alignment of the lower extremity in the presence of total knee endoprosthesis: reproducibility of torsion analyses using ultra-low-dose photon-counting CT. *Eur J Radiol* 2023;167:111055
64. Grunz JP, Heidenreich JF, Lennartz S, Weighardt JP, Bley TA, Ergün S, et al. Spectral shaping via tin prefiltration in ultra-high-resolution photon-counting and energy-integrating detector CT of the temporal bone. *Invest Radiol* 2022;57:819-825
65. Layer YC, Mesropyan N, Kupczyk PA, Luetkens JA, Isaak A, Dell T, et al. Combining iterative metal artifact reduction and virtual monoenergetic images severely reduces hip prosthesis-associated artifacts in photon-counting detector CT. *Sci Rep* 2023;13:8955
66. Patzer TS, Kunz AS, Huflage H, Gruschwitz P, Pannenbecker P, Afat S, et al. Combining virtual monoenergetic imaging and iterative metal artifact reduction in first-generation photon-counting computed tomography of patients with dental implants. *Eur Radiol* 2023;33:7818-7829
67. Sodickson AD, Keraliya A, Czakowski B, Primak A, Wortman J, Uyeda JW. Dual energy CT in clinical routine: how it works and how it adds value. *Emerg Radiol* 2021;28:103-117
68. Krauss B, Grant KL, Schmidt BT, Flohr TG. The importance of spectral separation: an assessment of dual-energy spectral separation for quantitative ability and dose efficiency. *Invest Radiol* 2015;50:114-118
69. Huflage H, Kunz AS, Hendel R, Kraft J, Weick S, Razinskas G, et al. Obesity-related pitfalls of virtual versus true non-contrast imaging—an intraindividual comparison in 253 oncologic patients. *Diagnostics (Basel)* 2023;13:1558
70. Rau A, Neubauer J, Taleb L, Stein T, Schuermann T, Rau S, et al. Impact of photon-counting detector computed tomography on image quality and radiation dose in patients with multiple myeloma. *Korean J Radiol* 2023;24:1006-1016
71. Pannenbecker P, Heidenreich JF, Grunz JP, Huflage H, Gruschwitz P, Patzer TS, et al. Image quality and radiation dose of CTPA with iodine maps: a prospective randomized study of high-pitch mode photon-counting detector CT versus energy-integrating detector CT. *AJR Am J Roentgenol* 2024;222:e2330154
72. Hayashi D, Roemer FW, Tol JL, Heiss R, Crema MD, Jarraya M, et al. Emerging quantitative imaging techniques in sports medicine. *Radiology* 2023;308:e221531
73. Stern C, Graf DN, Bouaicha S, Wieser K, Rosskopf AB, Sutter R. Virtual non-contrast images calculated from dual-energy CT shoulder arthrography improve the detection of intraarticular loose bodies. *Skeletal Radiol* 2022;51:1639-1647
74. Cook J, Rajendran K, Ferrero A, Dhillon P, Kumar S, Baffour F. Photon counting detector computed tomography: a new frontier of myeloma bone disease evaluation. *Acta Haematol* 2023;146:419-423
75. Winkelmann MT, Hagen F, Le-Yannou L, Weiss J, Riffel P, Gutjahr R, et al. Myeloma bone disease imaging on a 1st-generation clinical photon-counting detector CT vs. 2nd-generation dual-source dual-energy CT. *Eur Radiol* 2023;33:2415-2425
76. Symons R, Krauss B, Sahbaee P, Cork TE, Lakshmanan MN, Bluemke DA, et al. Photon-counting CT for simultaneous imaging of multiple contrast agents in the abdomen: an in vivo study. *Med Phys* 2017;44:5120-5127
77. Pannenbecker P, Huflage H, Grunz JP, Gruschwitz P, Patzer TS, Weng AM, et al. Photon-counting CT for diagnosis of acute pulmonary embolism: potential for contrast medium and radiation dose reduction. *Eur Radiol* 2023;33:7830-7839
78. Jost G, McDermott M, Gutjahr R, Nowak T, Schmidt B, Pietsch H. New contrast media for K-edge imaging with photon-counting detector CT. *Invest Radiol* 2023;58:515-522
79. Amato C, Susenburger M, Lehr S, Kuntz J, Gehrke N, Franke D, et al. Dual-contrast photon-counting micro-CT using iodine and a novel bismuth-based contrast agent. *Phys Med Biol* 2023;68:135001
80. Schwartz FR, Alkadhi H. Photon-counting detector CT for abdominal imaging: opportunities and challenges. *Eur Radiol* 2023;33:7805-7806