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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

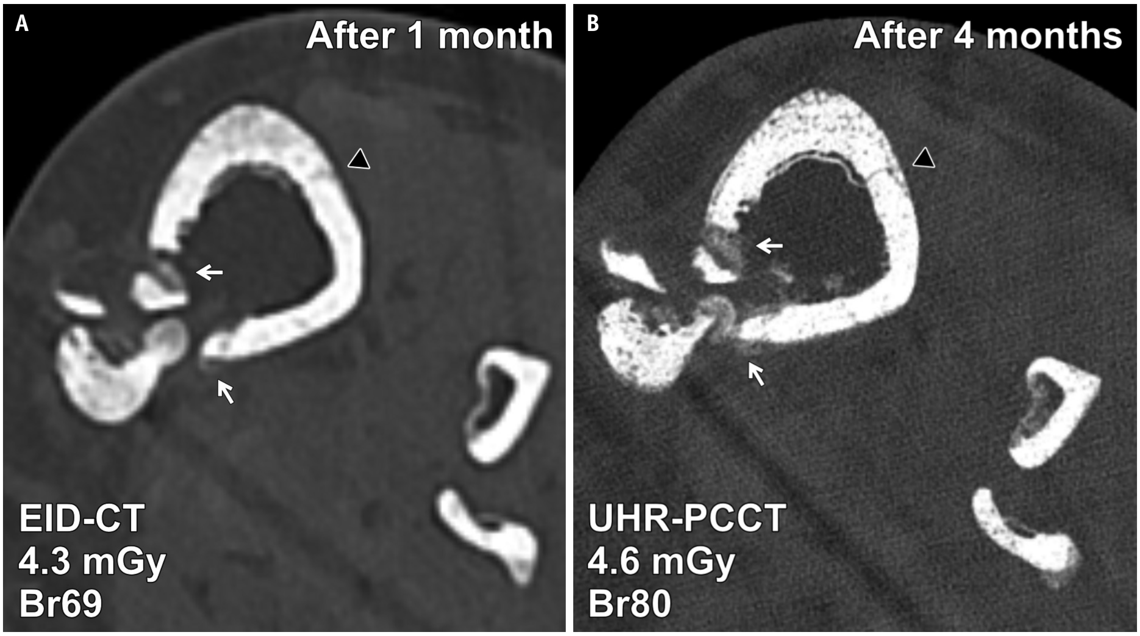

Fig. 2. A 29-year-old male was involved in a motorcycle accident, suffering a displaced multi-fragment injury of his left lower leg. **A, B:** UHR-PCCT at 140 kVp **(B)** allows for superior discrimination of bone microarchitecture (arrowheads) and callus formation over time (arrows) compared with standard-resolution 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

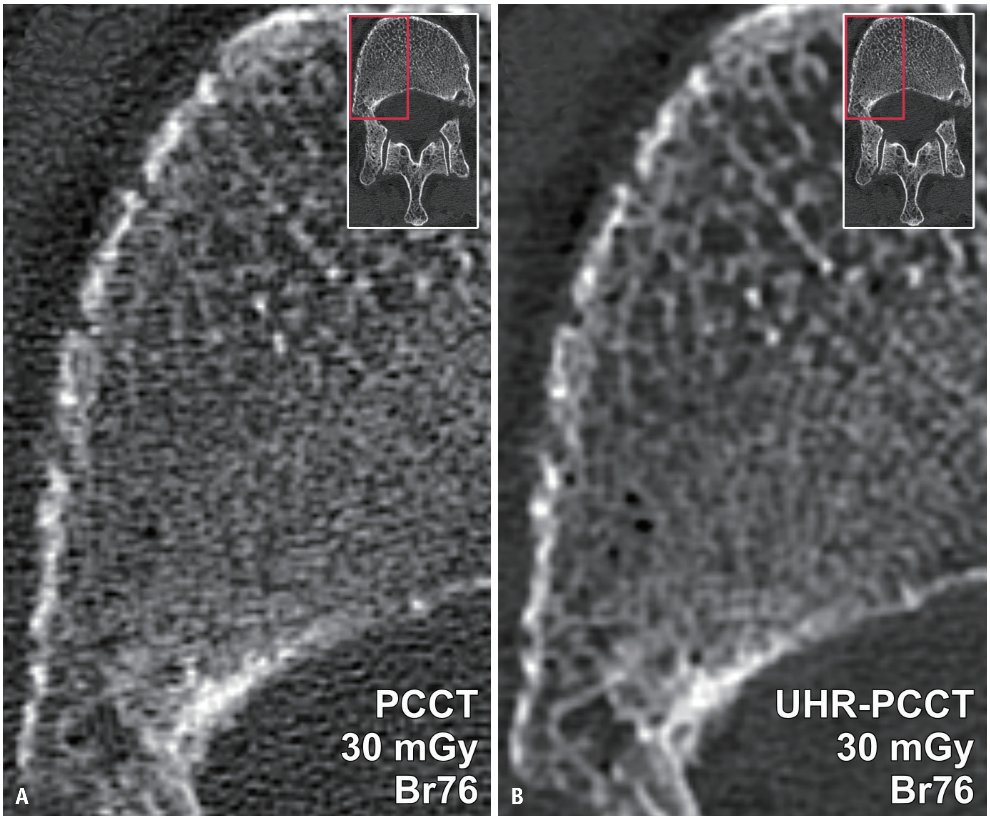

Fig. 3. Magnified side-by-side comparison of the trabecular microarchitecture in the third lumbar vertebra of a cadaveric specimen. **A, B:** Standard-resolution **(A)** and UHR-PCCT data **(B)** acquired at 140 kVp were reconstructed with the sharpest convolution kernel available for both scan modes. 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

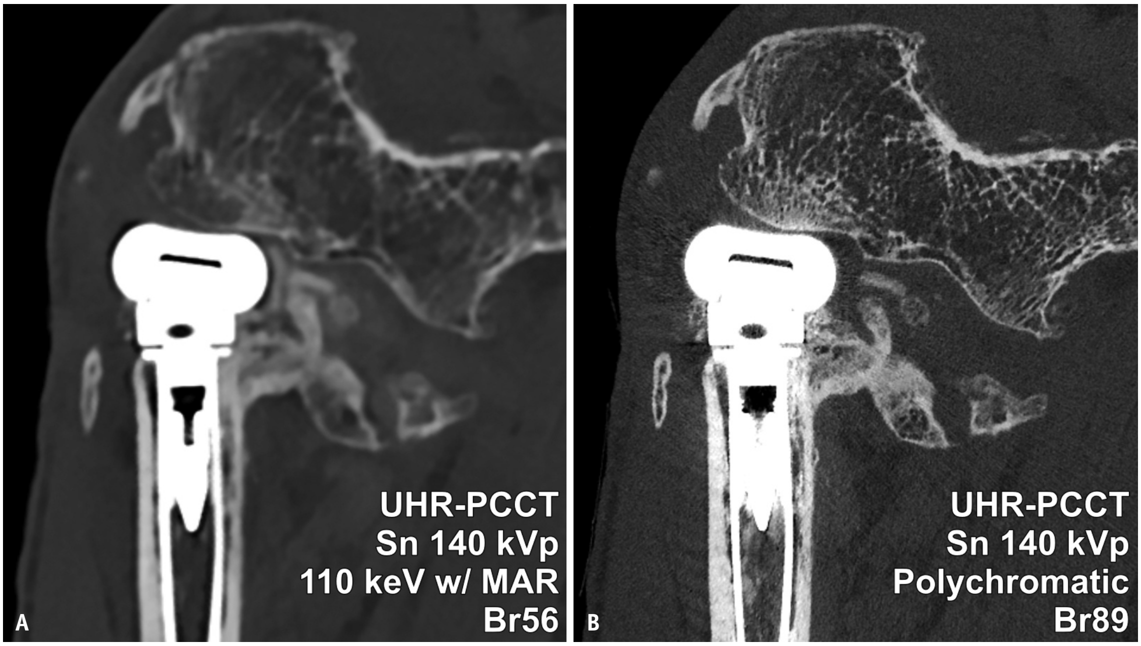

Fig. 4. UHR-PCCT elbow scan with tin prefiltration at 140 kVp in a 66-year-old female after radial head replacement. **A, B:** Whereas the combination of virtual monoenergetic imaging at 110 keV and MAR postprocessing allows for superior artifact reduction **(A)**, the limited reconstruction sharpness 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

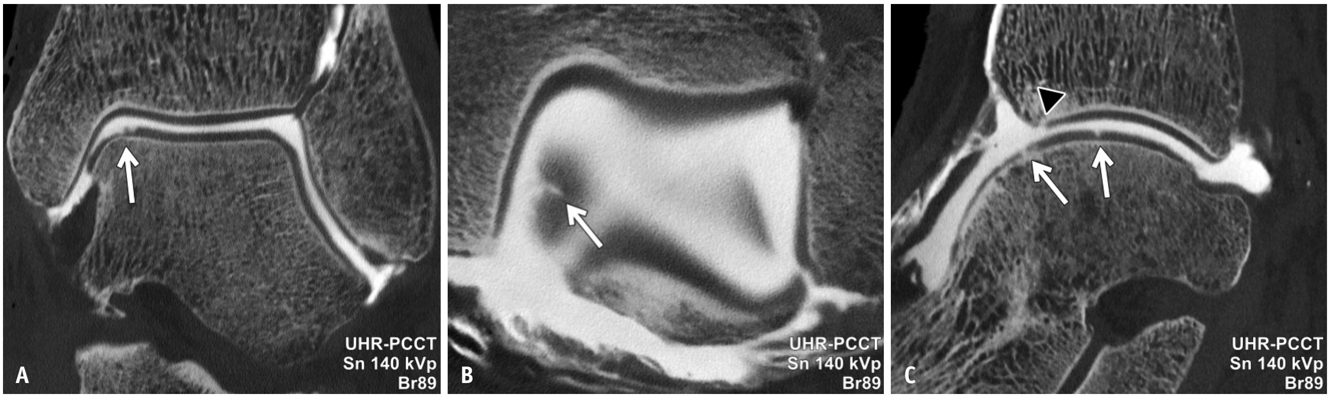

Fig. 5. UHR-PCCT arthrography of the left ankle of a 58-year-old female. **A-C:** While the articular injection of iodine-based contrast agent aids the depiction of minute cartilage injuries of the talus bone (arrows) and distal tibia (arrowhead), the virtual subtraction of contrast material may be helpful 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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