SSC12

Physics (Computed Tomography II: Dual-energy/Spectral CT)

Scientific Papers

PH CT

AMA PRA Category 1 Credits ™: 1.50

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Participants

Moderator
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Sub-Events

SSC12-01 Comparison of Estimated Organ Doses with Two Radiation Dose Estimation Software

Atul Padole MD (Presenter): Nothing to Disclose , Sarabjeet Singh MD : Research Grant, Siemens AG Research Grant, Toshiba Corporation Research Grant, General Electric Company Research Grant, Koninklijke Philips NV , Yiming Gao : Nothing to Disclose , Ranish Deedar Ali Khawaja MD : Nothing to Disclose , Diego Alfonso Lira MD : Nothing to Disclose , Mannudeep K. S. Kalra MD : Nothing to Disclose , Madan M. Rehani : Nothing to Disclose , Da Zhang PhD : Nothing to Disclose , Bob Liu PhD : Nothing to Disclose , George Xu PhD : Nothing to Disclose

PURPOSE

To compare the estimated organ doses obtained from two radiation dose estimation software for chest CT examinations in adult patients of different sizes.

METHOD AND MATERIALS

In an IRB-approved, HIPAA compliant study, we included 60 patients (mean age: 62 ± 9 years; M: F=29:31) undergoing chest CT for lung nodule follow up on a 16-slice MDCT (GE LightSpeed Pro 16). Based on weight, patients were divided into 3 groups (20 patients each); < 61 kg, 61-91 kg, and > 91 kg. Automatic dose monitoring software, eXposure (Radimetrics Inc.) and VirtualDose (Virtual Phantoms, Inc.) were used to obtain patients' organ doses. Organ doses for following organs adrenal glands, breast, esophagus, heart, lungs, stomach, liver, spleen, and kidney were recorded form two software was calculated. Scan parameters including kV, fixed mAs, scan length, rotation time, pitch, and beam collimation, CTDIvol, and DLP were also recorded. The difference between organ doses obtained from software. Paired t-tests were used to compare difference in the organ doses, P-value of 0.05 with 95% confidence interval was considered significant.

RESULTS

The mean CTDIvol were 3.2 mGy (<61 kg), 4.8 mGy (61-91 kg), and 7 mGy (>91 kg). The organ doses for adrenal glands, breast, esophagus, heart, lungs, stomach, liver, spleen, and kidney obtained from eXposure were significantly greater compared to organ doses obtained from VirtualDose software ($p<0.001$). Mean (± standard deviation) difference in organ doses between the both software were 1.24 ± 0.6 mSv (<61 kg), 2.1 ± 0.8 mSv (61-91 kg), 3.9 ± 1.2 mSv (>91 kg) ($p<0.001$). The minimum and maximum difference in organ doses estimated with the two software was for adrenal (12-14%) and esophagus (53-61%), respectively.

CONCLUSION

The organ doses obtained from eXposure software were substantially greater compared to VirtualDose software for patients with different weight group. Marked difference in the organ doses was noted for patients with greater body weight.

CLINICAL RELEVANCE/APPLICATION

Accurate determination of patient size is important for estimating organ doses as observed with radiation dose estimating software.

SSC12-02 Differentiation of Low-attenuation Intracranial Hemorrhage and Calcification Using Dual-energy Computed Tomography in a Phantom System

Jessica Lee Nute MS (Presenter): Nothing to Disclose , Megan Jacobsen : Nothing to Disclose , Dawid Schellingerhout MD : Nothing to Disclose , Jim W. Pennington : Nothing to Disclose , Adam Grant Chandler PhD : Employee, General Electric Company , Dianna D. Cody PhD : In-kind support, General Electric Company

PURPOSE

Intracranial hemorrhage and calcification with Single-Energy CT (SECT) attenuation levels below 100 HU cannot be reliably differentiated using currently clinically available means. Calcification is typically benign but hemorrhage can carry a risk of intracranial bleeding and contraindicate use of anticoagulant therapies. A biologically relevant phantom was constructed to examine the effects of lesion size, lesion location, and scan technique on the differentiating power of Dual-Energy CT (DECT).

METHOD AND MATERIALS

Spectrally-equivalent brain material was fit into the cranial cavity of an anthropomorphic head phantom. Cylindrical lesion models (diameters: 0.5, 1.0 and 1.5cm) were created by adding calcium carbonate or ferric oxide to the background brain material. Seven sets of lesion models were created at matched SECT HUs from 40 to 100HU. Lesion models of each size were placed in the cerebrum, while just the largest lesion size was placed in the skull base. The phantom was scanned using a SECT routine brain protocol to verify the HU matching of the lesions as well as five DECT protocols representing CTDIvol levels from 27 to 81mGy each using four image thicknesses: 1.25, 2.5, 3.75 and 5mm. Each scan was reconstructed using a water/calcium material density pair. A two-component, 3D Gaussian mixture model was applied using a 50/50 training/validation approach. Accuracy of differentiation was calculated by comparing predicted voxel assignments with actual voxel identities.

RESULTS

Accuracy of differentiation improved with increasing dose, image thickness and lesion size. Accuracy was also notably poor in the skull base region. Using our current analysis method, differentiation was feasible in the cerebrum down to 70HU with close to 90% accuracy when 5mm images and 67mGy CTDIvol were applied to the 1.5cm lesions.

CONCLUSION

SEHU matched hemorrhage and calcification models less than 100HU could be distinguished using DECT. Future work will include expanded scan acquisition parameter sets and more sophisticated statistical analysis, which may provide stronger results.

CLINICAL RELEVANCE/APPLICATION

The ability to distinguish between intracranial calcifications and hemorrhages using dual energy CT may help guide the use of anti-coagulant medications.

SSC12-03

Dose Efficiency of Virtual Non-contrast Imaging from Optimal kV Combination in Dual-energy CT

Lifeng Yu PhD (Presenter): Nothing to Disclose , Joshua Grimes PhD : Nothing to Disclose , Shuai Leng PhD : Nothing to Disclose , Joel Garland Fletcher MD : Grant, Siemens AG , Cynthia H. McCollough PhD : Research Grant, Siemens AG

PURPOSE

The purpose of this work was to determine the dose efficiency of virtual non-contrast (VNC) imaging from various kV combinations in dual-energy (DE) CT if the VNC were to replace the true non-contrast (TNC) scan, and to select the optimal kV combination for different patient attenuation levels.

METHOD AND MATERIALS

VNC image quality is fundamentally limited by the noise magnification in the material decomposition, which is determined by both the spectrum separation and the noise in the original low- and high-kV images. For the commercially available 5 DE kV combinations: 70/150Sn ("Sn": an added tin filter), 80/150Sn, 90/150Sn, 100/150Sn, and 80/140, we derived the lowest noise on the VNC image that is achievable when the optimal dose fractions at low- and high-kV scans were used, given a fixed total radiation output. The lowest VNC noise was compared with the noise in optimally mixed images to calculate the percent of dose reduction at each kV combination if VNC were to replace the TNC scan. The effect of patient attenuation was studied by scanning a series of semi-anthropomorphic phantoms with lateral width of 25, 30, 35, 40, 45, and 50 cm at each of the 5 kV combinations. To determine the optimal DE kV combination used for each phantom size, the noise power spectrum (NPS) at each lower kV was measured and compared with a reference single energy 120 kV, and the artifacts due to photon starvation, if any, were analyzed. Finally, the dose reduction by VNC at each kV combination for the applicable phantom sizes was determined.

RESULTS

The optimal DE kV combination was determined for each phantom size (25 cm: 70/Sn150, 30 cm: 80/Sn150, 35 cm: 80/Sn150, 40 cm: 90/Sn150, 45 cm: 100/Sn150, 50 cm: none). The dose reduction achievable by VNC increases with more separation of the spectra between low- and high-kV x-ray beams. For a 25 cm phantom that all kV are applicable, the dose reductions were 39%, 35%, 30%, 27%, and 10% for 70/150Sn, 80/150Sn, 90/150Sn, 100/150Sn, and 80/140, respectively.

CONCLUSION

With the optimal DE kV combination, radiation dose reduction achievable by using VNC to eliminate the true

non-contrast scan increases from 10% to up to 39% for adult patients.

CLINICAL RELEVANCE/APPLICATION

Optimal DE kV combination was determined for different patient attenuation levels. The amount of dose reduction achievable by VNC imaging increases from 10% to up to 39% for adult patients when using these optimal DE kV combinations.

SSC12-04

Use of Dynamic Focal Spot Control to Reduce Focal Spot Blooming in CT, and Its Impact on High-contrast Spatial Resolution

Xinhui Duan PhD : Nothing to Disclose , Joshua Grimes PhD (Presenter): Nothing to Disclose , Lifeng Yu PhD : Nothing to Disclose , Shuai Leng PhD : Nothing to Disclose , Cynthia H. McCollough PhD : Research Grant, Siemens AG

PURPOSE

To measure the effect of focal spot blooming on CT spatial resolution, and to evaluate the ability of quadrapole dynamic focusing to counteract focal spot blooming as x-ray tube current and potential are changed.

METHOD AND MATERIALS

High-contrast spatial resolution was evaluated 1) in-plane by scanning a wire phantom (tantalum wire, 0.125 mm diameter, suspended in air) to measure modulation transfer function (MTF) and 2) along the z-axis by scanning a foil phantom (50 micron thick, 1 mm diameter gold foil) to measures slice sensitivity profile (SSP). Phantoms were scanned at 70-150 kV on a Siemens Force scanner with dynamic focal spot control, and 70-140 kV on a Siemens Definition Flash scanner, with tube current ranging from 100 mA to the maximum available on each system. Images were reconstructed using 0.6 mm image thickness and 50 mm field-of-view with smooth (Force: Br36 and Flash: B30) and sharp (Force: Br64 and Flash: B70) kernels.

RESULTS

The variation in spatial resolution in the axial plane was much smaller on Force scanner than the Flash scanner as tube current and voltage changed. Comparing the spatial frequencies at the 50% values of the MTF curves, the difference between the minimum and maximum values for all kV-mA combinations was 3.0% for the smooth kernel and 4.7% for the sharp kernel on the Force scanner. These values were 10.5% and 21.9%, respectively, for the Flash scanner. The full-width-at-half-maximum (FWHM) of the SSP increased on both systems, but increased more slowly as tube current increased on the Force scanner (0.096 mm and 0.11 mm per 1000 mA for the smooth and the sharp kernels, respectively) than the Flash scanner (0.19 mm and 0.17 mm per 1000 mA).

CONCLUSION

The x-ray tube equipped with dynamic focal spot control on a recently-introduced scanner greatly reduced blooming effects, keeping the in-plane spatial resolution constant over a large range of tube currents and voltages.

CLINICAL RELEVANCE/APPLICATION

Technical measures to limit focal spot blooming are important, especially at low kV and high mA, which is relevant in children and smaller adults, and for dual-energy scanning.

SSC12-05

Value of an Advanced Image-based Technique to Calculate Virtual Monoenergetic CT Images Using Third-generation Dual-energy Dual-source CT to Improve Contrast-to-Noise Ratio in Liver Examinations

Carlo Nicola de Cecco MD (Presenter): Nothing to Disclose , James Spearman : Nothing to Disclose , U. Joseph Schoepf MD : Research Grant, Bracco Group Research Grant, Bayer AG Research Grant, General Electric Company Research Grant, Siemens AG , Christian Canstein : Employee, Siemens AG , Felix G. Meinel MD : Nothing to Disclose , Andrew D. Hardie MD : Nothing to Disclose , Philip Costello MD : Nothing to Disclose

PURPOSE

To evaluate whether a dedicated image-based algorithm for virtual monoenergetic imaging (Mono+) with a third-generation dual-energy, dual-source CT scanner can improve the contrast-to-noise ratio (CNR) of liver parenchyma in comparison with a standard virtual monoenergetic algorithm and also 100 and 120kV polyenergetic data-sets.

METHOD AND MATERIALS

Eight patients underwent abdominal CT examinations including single-energy unenhanced (120kV, 147ref.mAs) and dual-energy portal phase (100/Sn150kV, 180/90ref.mAs) imaging. Dual-energy data were processed, and virtual monoenergetic images (range, 40-120/150/190keV) were generated using both standard monoenergetic and Mono+ algorithms. The new algorithm performs a regional analysis-dependent frequency-based recombination of the high signal at lower energies and the superior noise properties at medium energies to optimize CNR and avoid the noise increases at lower calculated energies which are commonly observed with

standard algorithms. Liver parenchyma and intrahepatic portal vein attenuation and image noise were measured and the CNR was subsequently calculated. Differences in liver attenuation and CNR were compared between the different virtual monoenergetic datasets and the standard 100 and 120kV polyenergetic datasets.

RESULTS

For Mono+, the optimum CNR was obtained at the lowest energy level of 40keV (10.9± 13.5HU) while the optimum CNR of the standard monoenergetic algorithm was at 70keV (5.7 ± 28.0HU). The CNR of Mono+ reconstructions was 47% greater than with the standard monoenergetic algorithm. Compared with the corresponding standard 40 keV data-set, the incremental improvement in CNR was even higher (3.6 ± 15.8HU, 67% increment). The optimum Mono+ CNR at 40keV was also significantly higher than the CNR in the standard 120kV polyenergetic data-set (4.0 ± 50.3HU, 63% improvement) and in the 100kV data-set (5.7 ± 40.9HU, 39% improvement). In fact, all Mono+ data-sets from 40 to 70keV had a CNR significantly higher than the optimum standard monoenergetic reconstructions at 70keV as well as the 100 and 120kV polyenergetic datasets.

CONCLUSION

Mono+ virtual monoenergetic images have a significantly higher CNR for liver CT imaging compared with both standard virtual monoenergetic algorithms and 100 and 120 kV polyenergetic images.

CLINICAL RELEVANCE/APPLICATION

Mono+ improves the quality of virtual monoenergetic images, which may enhance diagnostic performance and reduce contrast medium volumes.

SSC12-06 Preliminary Results of a Prototype Quality Control Process for Spectral CT

Jessica Lee Nute MS (Presenter): Nothing to Disclose , Megan Jacobsen : Nothing to Disclose , Jim W. Pennington : Nothing to Disclose , Adam Grant Chandler PhD : Employee, General Electric Company , Yasuhiro Imai MS : Employee, General Electric Company , Dianna D. Cody PhD : In-kind support, General Electric Company

PURPOSE

A prototype quality control (QC) phantom and analysis process has been designed specifically to monitor dual-energy CT and address the current lack of quantitative oversight of the spectral capabilities of these scanners.

METHOD AND MATERIALS

A prototype solid water phantom was designed with multiple material inserts, and to support both head and body protocols. Inserts included tissue equivalent and material rods (iodine, iron, calcium) at various concentrations. The oval body phantom, measuring 30cmx40cmx15cm, was scanned using four dual-energy protocols with CTDIvol ranges of 19.6-62mGy (0.516 pitch) and 10.3-32.5mGy (0.984 pitch), and rotation times ranging from 0.5-1sec. The circular head phantom, measuring 22cm in diameter by 15cm, was scanned using three dual-energy protocols with CTDIvol ranges of 67-132.6mGy (0.531 pitch) and 36.7-72.7mGy (0.969 pitch), and rotation times ranging from 0.5-0.9sec. All images were reconstructed at 50, 70, 110 and 140 keV, and using a water-iodine material basis pair. The images were evaluated for iodine quantification accuracy and stability of monoenergetic reconstructions. The phantom was scanned twice on ten GE 750HD CT scanners to evaluate inter-scanner agreement, as well as ten times on a single scanner over a one-week period to evaluate intra-scanner repeatability.

RESULTS

Preliminary analysis revealed consistent (inter- and intra-scanner) iodine quantification accuracy within 10% was only achieved for protocols in the upper half of dose levels assessed when grouped by pitch. Although all scanners undergo rigorous daily single-energy QC, iodine quantification accuracy from one scanner unexpectedly deviated from the other nine substantially. In general, inter-scanner agreement and intra-scanner repeatability varied with dose, rotation time and reconstructed keV.

CONCLUSION

Preliminary results indicate the need for a dual-energy QC process to ensure inter-scanner agreement and intra-scanner repeatability. In particular, iodine quantification accuracy should be monitored, particularly for lower dose techniques. Future plans include longer term dual-energy CT QC data collection.

CLINICAL RELEVANCE/APPLICATION

DECT is quickly becoming a critical part of routine exams. QC such as quantitative accuracy and long term stability haven't been addressed but are essential to ensuring confidence in this application.

SSC12-07 Incremental Benefit and Clinical Significance of Retrospectively Obtained Spectral Data in a Novel Spectral Detector CT Technology- Initial Experiences and Results

Claudia M. Martinez Rios Arellano MD : Research Grant, Koninklijke Philips NV , Rong Rong MD : Institutional Grant support, Koninklijke Philips NV , Robert C. Gilkeson MD : Research Consultant, Riverain

Technologies, LLC Research support, Koninklijke Philips NV Research support, Siemens AG , Luis Alberto Landeras MD : Institutional Grant support, Koninklijke Philips NV , Prabhakar Rajiah MD, FRCR (Presenter): Institutional Research Grant, Koninklijke Philips NV

PURPOSE

To evaluate the incremental benefit and clinical significance of the availability and utility of spectral reconstruction data with spectral detector CT technology.

METHOD AND MATERIALS

Seventy-eight adult patients (34 female, 44 male) were prospectively scanned at the Spectral Detector-based CT (SDCT Philips Healthcare) scanner technology. Clinical indication was noted and two radiologists made unanimous decision if a dual energy acquisition would have been requested in advance of the scan. The CT images with spectral reconstructions were evaluated for clinical findings, artifacts and image quality. Readers selected which cases would benefit from spectral reconstructions and the type of reconstruction was indicated. Clinical significance of the spectral reconstructions was graded as 0- no significant; 1- low; 2- intermediate, 3-moderate; and 4-highly significant.

RESULTS

8 CT of chest, 29 abdomen, 9 chest, abdomen, pelvis, 31 angiograms and 1 spine were included. A dual energy mode would have been prospectively clinically indicated in 15 patients (19%). However, readers requested retrospective spectral reconstructions in 67 patients (84.6 %). A total of 183 additional reconstructions with high monoenergy (monoE) images in 72 instances [(39.34%), 51 cases, 65.3%]; low monoE in 35 instances [(19.13%), 35 patients, 44.8%]; iodine-only images in 44 instances [(39.34%), 42 patients, 53.8%]; virtual non contrast in 17 instances [(9.29%), 17patients, 21.8%]; effective-z in 15 instances [(8.19%), 15 patients,19.2 %] were required. Additional spectral reconstructions were required on average 2.3 instances per patient. High monoE images were clinically useful in 56.94% for artifact reduction; low monoE in 44.8% for vascular contrast boost; iodine-only images in 15.9% for cystic and solid lesions evaluation 61.36%; and effective z for stone analysis in 33.3%. Clinical significance was rated as 0 in 10.38%, 1 in 36.1%, 2 in 29.51%, 3 in 20.21% and 4 in 3.82%.

CONCLUSION

Additional retrospective CT data reconstructed from SDCT scanner improves the diagnostic capabilities mainly for eliminating artifacts, improving contrast in vascular structures and characterizing lesions.

CLINICAL RELEVANCE/APPLICATION

Spectral detector-CT allows retrospective reconstruction and improved diagnostic capabilities even in patients who would not have been preselected for a DECT technique.

SSC12-08 Performance of Today's Dual Energy CT and Future Multi Energy CT in Virtual Non Contrast Imaging and in Iodine Quantification

Sebastian Faby DIPLPHYS (Presenter): Nothing to Disclose , Stefan Kuchenbecker MENG : Nothing to Disclose , David Simons MD : Nothing to Disclose , Heinz-Peter Schlemmer MD : Nothing to Disclose , Michael Marcus Lell MD : Research Grant, Siemens AG Speakers Bureau, Siemens AG Research Grant, Bayer AG Speakers Bureau, Bayer AG Research Consultant, Bracco Group , Marc Kachelriess PhD : Nothing to Disclose

PURPOSE

To compare the performance of different state-of-the-art dual energy CT (DECT) techniques with novel photon counting (PC) multi energy CT (MECT) with respect to dose efficiency in contrast-enhanced imaging.

METHOD AND MATERIALS

A typical spectral CT application is the decomposition of CT data into virtual non-contrast (VNC) and iodine overlay images. We study its dose efficiency given that a number of spectral CT implementations are available and that others may become available. Different clinical DECT implementations were simulated: dual source, rapid kV switching and sandwich detector DECT. We further simulated promising types of realistic PC detectors with a variable number of energy bins. We also simulated dual source systems with one or two detectors being PC. For our simulation patient data were decomposed and a polychromatic forward projection yields the corresponding rawdata. Statistically optimal material decomposition [Faby et al., SPIE 2014] was employed to guarantee a fair comparison of all modalities. Dose, spatial resolution and contrast were the same among the modalities and thus it is sufficient to compare image noise which can then be converted into dose reduction values.

RESULTS

Results are expressed with dual source DECT at 100 kV/140 kV Sn (tin prefilter) being the reference. Using dual source settings of 90 kV/150 kV Sn led to a dose reduction of -39% VNC/-45% iodine. This is comparable to the performance of an ideal PC detector with two energy bins. Using eight energy bins results in -48%/-75%. Sandwich detector DECT at 140 kV is showing a dose increase +56%/+92%. A realistic PC detector with two energy bins performs as the sandwich detector for the VNC image but much better for the iodine image (+58%/+11%). Rapid kV switching with 80 kV/140 kV evaluated to +73%/-15%. Due to a lack of space we will present results for other spectral CT implementations at the meeting.

CONCLUSION

The results indicate significant patient dose saving possibilities for dual source CT settings of 90 kV/150 kV Sn (-39%/-45%) and an ideal PC detector with two energy bins (-29%/-59%). Using more than two energy bins improves the results further. Degrading effects in the PC detector set this technology back to the level of today's DECT.

CLINICAL RELEVANCE/APPLICATION

Dose saving possibilities for the patient in the context of contrast agent enhanced imaging are evaluated based on different dual and multi energy techniques.

SSC12-09

Dual-Energy Imaging of Bone Marrow Edema on a Dedicated Extremities Cone-Beam CT System

Wojciech Zbijewski PhD (Presenter): Research Grant, Carestream Health, Inc , Alejandro Sisniega PhD : Research Grant, Carestream Health, Inc , Joseph Webster Stayman PhD : Research Grant, Varian Medical Systems, Inc , Gaurav Kumar Thawait MD : Nothing to Disclose , Shadpour Demehri MD : Nothing to Disclose , Jan Fritz MD : Research Grant, Siemens AG Research Consultant, Siemens AG , Jeffrey H. Siewerdsen PhD : Research Grant, Siemens AG Consultant, Siemens AG Research Grant, Carestream Health, Inc Royalties, Elekta AB

PURPOSE

Bone marrow edema (BME) is an important biomarker of arthritis and bone trauma. BME presents as increased fluid content and decreased fat content in the cancellous bone and is challenging to detect in x-ray CT due to trabecular structure. Virtual noncalcium (VNC) images obtained using Dual Energy (DE) enable visualization of BME in conventional CT. We investigate the feasibility of DE imaging of BME on a dedicated flat-panel detector extremities cone-beam CT (CBCT).

METHOD AND MATERIALS

DE CBCT imaging was performed at 0.278 mm pixel pitch and 480 projections over 240o using a low energy (LE) beam of 70 kVp, 120 mAs/scan (~9.6 mGy), and a high energy (HE) beam of 120 kVp, 48 mAs/scan (~19 mGy). Due to power limitations of the x-ray tube (max. 0.875 kW), no high-Z filtration could be applied to the HE beam to increase energy separation. Reconstructions were obtained at 0.5 mm voxels using FBP and penalized-likelihood with Huber penalty (PLH). Reconstruction-based three-material DE decomposition yielded volume fractions of soft tissue, fat, and bone. A computer simulation study with polyenergetic projections of a digital BME knee phantom was performed. Experimental studies involved a 12 cm water phantom with two bone inserts (50 mg/mL $CaCO_3$) embedded in water and alcohol (simulating fat). Each insert contained a pattern of 1 mm - 4 mm cavities filled with the surrounding fluid to emulate the trabecular matrix.

RESULTS

DE noncalcium soft-tissue images correctly identified 76% of the area of simulated BME at realistic levels of projection noise (corresponding to bare beam signal of 10^5-10^6 photons/pixel). The experimental studies show discrimination of water and fat even in the presence of partial volume effects and resolution blur in the vicinity of the cavities of bone inserts. PLH performed slightly better than FBP, reducing the error in estimation of the total fat area from 46% for FBP to 19% for PLH at similar noise levels in the VNC image.

CONCLUSION

Detection of BME and quantification of water and fat content using DE were demonstrated on the extremities CBCT, opening a broad range of diagnostic applications in e.g. detection and staging of arthritis.

CLINICAL RELEVANCE/APPLICATION

DE detects BME in extremities CBCT, overcoming a major limitation of single energy imaging and enabling novel diagnostic applications in rheumatoid arthritis, osteoarthritis and bone trauma.