Bone Marrow Lesions in the Posttraumatic Ankle Joint: Comparison of Dual-Energy Computed Tomography with Magnetic Resonance Imaging

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Purpose

To evaluate prospectively, in patients with acute ankle joint trauma, the performance of non-calcium images reconstructed from dual-energy computed tomography (DECT) for the diagnosis of bone marrow lesions in comparison with magnetic resonance imaging (MRI).
Methods and Materials

This prospective study was approved by the local ethic committee.

Study Subjects
Between September 2010 and May 2011 a total of 32 consecutive patients (mean age 34.7 ±12.4 years; age range 19-63 years; 17 women) with acute ankle trauma were included. All patients were referred for CT due to the clinical suspicion of fracture and equivocal findings on standard radiographs. Exclusion criteria were age less than 18 years, pregnancy or contraindications to MR imaging (e.g. non-MR-compatible pacemakers), prior ankle trauma or surgery within one year to the current trauma and metal implants. In one patient, CT images suffered from severe cast-induced artifacts. Another patient left the hospital before MR images (Fig. 1).

Thus, final data from 30 patients (mean age 34 ±11.8 years; age range 19-63 years; 15 women) was available for analysis.

CT Protocol
All CT scans were performed on a second generation 128-section dual-source CT machine (Somatom Definition Flash, Siemens Healthcare, Forchheim, Germany).

CT acquisitions were performed in craniocaudal direction using a dual-energy protocol (collimation, 40 x 0.6 mm; pitch, 0.7; rotation time, 1 s). Tube voltages were set at 80 kVp (tube A) and 140 kVp (tube B), with activated tin (Sn)-filtering for tube B (20).

The predefined tube current-time product was set at a ratio of approximately 2:1 (tube A, 360 effective (eff) mAs; tube B, 180 eff mAs), with automated attenuation-based tube current modulation (CAREDose4D).

The CT dose index (CTDInvol) of this protocol according to the patient protocol was 15 ± 1 mGy (range, 13-16 mGy), the mean dose-length product was 257 ± 42 mGycm (range, 186-380 mGycm). No intravenous contrast agent was administered.

CT Image Reconstruction and Post-processing
By default three different image sets were generated from each DECT scan: a 80 kVp-set, a Sn140 kVp-set, and a weighted average-set at a ratio of 0.4:0.6. Transverse images were reconstructed for all three data sets with a section thickness of 2 mm and 1 mm increment, using a bone- (B70s) and soft-tissue convolution kernel (D30s). Additionally, transverse thin-slice images (0.75 mm slice thickness, increment 0.5 mm, B70s) were reconstructed.

Post-processing was performed using commercially available software (Syngo Dual Energy, version VA34A; Siemens) and a three-material decomposition algorithm for bone mineral, yellow and red marrow. The algorithm used a relative contrast ratio of 1.75,
based on the experiences from a previous study using dual energy spectra at 80 and 140kV but no tin-filtering [1]. The range of the smoothing filter was 3 (Fig. 2). Only voxels with HU values ranging between -300 and 900 on the weighted average images were analyzed to improve discrimination of traumatic from normal bone marrow. Non-calcium images were displayed in gray-scale and in color-coded maps (parathyroid setting of the software) for further analysis.

MR Imaging Protocol
All patients underwent MR imaging using a 1.5 Tesla scanner (Signa EXCITE HDx, GE Healthcare, Waukesha, WI, USA) and a dedicated 8-channel ankle-coil (HD foot/ankle array, Invivo, Gainesville, FL, USA). The standard MR imaging protocol as used at our institution for all patients with ankle trauma was applied:

- **sagittal T1-weighted spin-echo MR sequence** (repetition time (TR)/echo time (TE), 500/12 ms; echo-train-length (ETL), 3; field of view (FoV), 16x16 cm; acquisition matrix, 320x192; section thickness, 3 mm; intersection gap, 1 mm),
- **axial short tau inversion recovery (STIR) MR sequence** (TR/TE, 5000/34 ms; ETL, 16; FoV, 14x14 cm; acquisition matrix, 256x192; section thickness, 3 mm; intersection gap, 1 mm),
- **transaxial intermediate weighted MR sequence** (TR/TE, 3500/42ms; ETL, 9; FoV, 16x16 cm; acquisition matrix, 320x224; section thickness, 3 mm; intersection gap, 1 mm) and
- **coronal T2-weighted fat-saturated fast spin-echo (FSE) MR sequence** (TR/TE, 4000/102; ETL, 20; FoV, 16x16 cm; acquisition matrix, 256x192; section thickness, 3 mm; intersection gap, 1 mm).

Subjective Image Analysis
For all analyses, the ankle joint was sub-divided into 10 anatomic regions: 1 = lateral ankle; 2 = medial ankle; 3 = anterior tibial pilon; 4 = posterior tibial pilon; 5, 6 and 7 for lateral, intermediate and medial talar dome, respectively; 8 = posterior talar process; 9 = lateral talar process; and 10 = talar head (Fig 3).
First, two independent and blinded readers analyzed all CT images in random order. Each anatomic region was evaluated for the presence of traumatic bone marrow lesions on the non-calcium DECT images using a four-point classification system (Fig 4): 1 = distinct signs of abnormal bone marrow signal/attenuation, 2 = less pronounced changes, most probably representing a traumatic bone marrow lesion, 3 = equivocal, most probably no traumatic bone marrow lesion, and 4 = normal bone marrow.

As standard of reference, all MR images were evaluated for the presence of traumatic bone marrow lesions by a third experienced reader in random order. The reader was blinded to the CT results and used the same anatomic regions and classification system described above. The reader was free to change window level settings and magnification factor of the MR images.
**Objective Image Analysis**
Quantitative image analyses were performed by a fourth reader who was blinded to the results from the subjective image analysis. HU values were measured on non-calcium images from DECT using circular regions of interests (ROI) of 0.3 cm² area. Within each anatomic region, ROIs were positioned at the location with the highest attenuation on MR images.

**Statistical Analysis**
Interreader agreement for qualitative assessments of DECT images was calculated by using kappa-statistics.
Data from the four-point classification system of both DECT and MR imaging were dichotomized to allow for calculation of sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy for each reader including 95% confidence intervals (CI).

Two analyses with different cut-off values were performed:
First, the cut-off was set between grade of 2 and 3 with grades 1 and 2 considered to be positive and grades 3 and 4 to be negative for traumatic bone marrow lesions.

The second analysis used a cut-off between grade 1 and grades 2-4.

Four-point gradings from MR imaging and HU values were further subjected to receiver operating characteristic curve (ROC) analysis and calculations of the area-under-the-curve (AUC), with MR imaging as the reference standard.

The 10 anatomic regions which were analyzed separately were grouped into three anatomic areas:
ankle mortise (regions 1-4), talar dome (regions 5-7) and talar body/head (regions 8-10).

Two analyses were performed: The first one with MR imaging gradings 1 and 2 as positive and gradings 3 and 4 as negative for bone marrow lesions; the second one with MR imaging gradings 1 as positive and gradings 2-4 as negative for bone marrow lesions.

The cut-off HU values showing the highest accuracy for differentiation between normal and abnormal bone marrow was derived for both analyses and each anatomic area.

Normal distribution of HU values in different anatomic regions was confirmed with Kolmogorov-Smirnov-testing. Analysis of variance (ANOVA) with Bonferroni post-hoc comparisons were performed for analyzing differences between normal and abnormal
bone marrow signal in different anatomic regions and areas. A p-value < 0.05 was considered statistically significant.
Fig. 1: Flow chart of the study illustrates data analysis of anatomic regions. Two patients were excluded after computed tomography (CT) had been performed: One patient had substantial artifacts on CT images caused by a cast; one patient voluntarily left the hospital prior to magnetic resonance (MR) imaging. Only traumatic bone marrow lesions within 3mm from cortical bone were included.

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Fig. 2: Screenshot of the dual energy computed tomography (DECT) post-processing software showing the settings for generation of non-calcium images in the ankle joint.

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Fig. 3: Series of transaxial CT-images at four different levels through the ankle joint: (a) level of tibial pilon, (b) level of talar dome, (c) level of posterior and lateral talar process, and (d) level of talar head. Levels illustrate the 10 different anatomic regions which were used for qualitative and quantitative image analyses: 1 = lateral ankle; 2 = medial ankle; 3 = anterior tibial pilon; 4 = posterior tibial pilon; 5, 6 and 7 for lateral, intermediate and medial talar dome, respectively; 8 = posterior talar process; 9 = lateral talar process and 10 = talar head.

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Fig. 4: Representative examples of our grading system for non-calcium DECT images (left) and corresponding T2-weighted short-tau inversion recovery (STIR) MR images (right): (a) score 1 = distinct signs of abnormal bone marrow signal/attenuation (arrows) on DECT and MR images in the talar head (true positive); (b) score 2 = less pronounced changes, most probably representing a traumatic bone marrow lesion (arrows) on DECT but normal finding (score 4) on MR image in the lateral talar dome (false positive); (c) score 3 = equivocal, most probably no traumatic bone marrow lesion (arrows) on DECT with less pronounced changes on MR (score 2) in the posterior tibial pilon (false negative); and (d) score 4 = normal bone marrow on DECT and MR images (true negative).

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Results

MR Imaging

There were a total of 52 anatomic regions with traumatic bone marrow lesions that were included into the analyses. Traumatic bone marrow lesions were most frequently located in the talar head (n=13), in the medial (n=8) and lateral talar dome (n=7) and in the posterior talar process (n=6).

Subjective Image Analysis

The overall interobserver agreement for qualitative analysis of non-calcium images between readers was substantial (κ=0.66).

All bone marrow lesions

Including both grade 1 and 2 lesions according to MR imaging as positive into the analysis, 16 FN and 38 FP gradings occurred with DECT. Reader 1 achieved an overall sensitivity of 73.1%, a specificity of 87.5%, a PPV of 55.9%, a NPV of 93.8%, and an accuracy of 84.9%; reader 2 achieved values of 71.2%, 86.1%, 52.1%, 93.3% and 83.5% (Figs 5 and 6, Table 1), respectively, for the diagnosis of bone marrow lesions with DECT.

Of the 16 FN findings with DECT, 14 (87.5%) regions were graded with MR imaging as 2 (= less pronounced, most probable changes), whereas 2 (12.5%) regions were graded with MR imaging as 1 (= distinct signs). Of the 38 FP findings, 30 (78.9%) regions were graded with 3 (= equivocal, most probably no change), while 8 (21.1%) regions were graded with 4 (= no changes) with MR imaging.

Distinct bone marrow lesions

Including only grade 1 lesions according to MR imaging as positive into the analysis, sensitivity of DECT for both readers increased to 90%, specificity decreased to 81.6 and 80.5%, PPV decreased to 26.5 and 25.4%, NPV increased to 99.1% and accuracy remained at a similar level of 82.2 and 81.2% (see Table 1).

Objective Image Analysis

Significant differences in HU values on non-calcium images were found between regions positive for bone marrow lesions and those that were negative on MR images in all anatomic areas (ankle mortise, talar dome and talar body/caput, each p<.001).

Significant differences in HU values of positive regions on MR images between anatomic areas were present only between the ankle mortise and talar body/head (post-hoc analysis, p<.01) (Table 2, Fig 7).

In regions with no abnormality on MR imaging, significant differences in HU values on non-calcium images were seen between the three anatomic areas (ANOVA, p<.001), with a gradual increase from proximal to distal location in the ankle joint (lowest values in the ankle mortise, highest values in the talar body/head). Significant differences in
HU values of negative regions on MR images between anatomic areas were present for all three areas (post-hoc analysis, p<.001).

All bone marrow lesions
When MR gradings of 1 and 2 were counted as positive for bone marrow lesion and served as reference standard, ROC analyses revealed AUCs for HU values in the ankle mortise, talar dome and talar body/head of 0.735, 0.785 and 0.791, respectively. The cut-off values for the HU values with the highest sensitivity and specificity for the ankle mortise, talar dome and talar body/head were -80, -70, -39 HU, respectively (see Table 2, Fig 8).

Distinct bone marrow lesions
Including only grade 1 lesions from MR imaging as positive and the remainder (grade 2-4) as negative, ROC analyses revealed AUCs for HU values in the ankle mortise, talar dome and talar body/head of 0.973, 0.813 and 0.758, respectively. The cut-off values for the HU values with the highest sensitivity and specificity for the ankle mortise, talar dome and talar body/head were -52, -70, -35 HU, respectively (see Table 2, Fig 8).
Fig. 5: Series of four corresponding transaxial images at the level of the talar dome of the right ankle in a 24-year-old male patient with acute ankle trauma. (a) T2-weighted short-tau inversion recovery (STIR) MR image shows traumatic bone marrow lesion in the medial dorsal aspect of the talus (arrow). (b) Weighted-average image simulating single-energy CT shows a normal trabecular bone structure without fracture. Grey level-coded (c) and color-coded non-calcium DECT image (d) depict bone marrow abnormalities in the same area as seen on the MR image (true positive finding).

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Fig. 6: Series of four corresponding transaxial images at the level of the tibial pilon of the right ankle joint in a 40-year-old female patient with acute ankle trauma. (a) T2-weighted short-tau inversion recovery (STIR) MR image shows subtle bone marrow lesion in the lateral aspect of the anterior tibial pilon (arrow). (b) Weighted-average image simulating single-energy CT shows no fracture. Grey level-coded (c) and color-coded non-calcium DECT images (d) depict no bone marrow abnormalities, resulting in a false negative finding.
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Table 1: Diagnostic performance of non-calcium DECT images for the detection of traumatic bone marrow lesions of the ankle joint.

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Table 2: Analysis of HU values on non-calcium images from DECT for the diagnosis of bone marrow lesions compared to MR imaging as reference standard.
Fig. 7: Hounsfield units (HU) measured on non-calcium DECT images. Positive (blue boxes) and negative anatomic regions (green boxes) for bone marrow lesions in the three different anatomic areas according to MR imaging, including both grades 1 and 2 as positive into the analysis, are shown. Note significant increase in HU values for negative regions while HU values of pathologic/positive regions differed significantly only between ankle mortise and talar body/head.

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**Fig. 8:** Receiver operating characteristic curves for HU values from non-calcium DECT images measured in the ankle mortise (continuous line), talar dome (dashed line), and talar body/head (dotted line). (a) MR gradings of 1 and 2 were counted as positive for bone marrow lesion. Areas under the curve (AUC) were 0.735 for ankle mortise, 0.785 for talar dome, and 0.791 for talar body/head. (b) MR grading of 1 was counted as positive for bone marrow lesion. Areas under the curve (AUC) were 0.973 for ankle mortise, 0.813 for talar dome, and 0.758 for talar body/head.

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Conclusion

In conclusion, our study shows that distinct traumatic bone marrow lesions of the ankle joint can be diagnosed on non-calcium images from DECT, using either a subjective or objective grading system, with a high sensitivity and excellent NPV as compared to MR imaging. On the other hand, specificity and particularly the PPV of DECT for the diagnosis of traumatic bone marrow lesions of the ankle joint are low. This indicates a potential role of non-calcium images to rule-out distinct bone marrow lesions in patients with acute trauma to the ankle joint.
References
