Axial Spondyloarthritis: Dual-Energy Virtual Noncalcium CT in the Detection of Bone Marrow Edema in the Sacroiliac Joints

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Purpose: To determine the diagnostic performance of dual-energy virtual noncalcium (VNCa) CT in the detection of bone marrow edema in study participants with spondyloarthritis.

Materials and Methods: In this prospective study, 47 consecutive participants (mean age, 27 years; age range, 14–41 years [28 male; mean age, 24 years; age range, 14–37 years] [19 female; mean age, 29 years; age range, 17–41 years]) underwent dual-energy CT and 3.0-T MRI between April 2016 and December 2017. Two independent readers visually evaluated all sacroiliac joints for the presence of abnormal marrow attenuation on dual-energy VNCa images using a four-point classification system (0, no edema; 1, mild edema; 2, moderate edema; 3, severe edema). CT numbers on VNCa images were determined with region-of-interest–based quantitative analysis. MRI was the reference standard for presence of bone marrow edema.

Results: Sensitivity, specificity, and accuracy of readers 1 and 2, respectively, in the identification of bone edema at CT were 87% and 93% (48 and 51 of 55), 94% and 91% (32 and 31 of 34), and 90% and 92% (80 and 82 of 89). Interobserver agreement was excellent (κ = 0.81). CT numbers from VNCa images increased from no edema to severe edema (P < .001). The area under the receiver operating characteristic curve was 0.93 for reader 1 and 0.91 for reader 2 in differentiation of the presence of bone marrow edema from no edema. A cutoff value of −33 HU derived from reader 1 yielded overall sensitivity, specificity, and accuracy of 90% (49 of 55), 83% (28 of 34), and 87% (77 of 89) in the detection of any extent of edema in the sacroiliac joints.

Conclusion: Dual-energy VNCa CT images had excellent diagnostic performance in evaluation of the extent of bone marrow edema in study participants with spondyloarthritis associated with axial spondyloarthritis.

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In the management of symptomatic axial spondyloarthritis (axSpA), it is important to accurately monitor current disease activity and the extent of structural damage (1). Recent European League Against Rheumatism recommendations on the use of MRI in patients with axSpA show that this imaging modality should be considered for use in the detection of both subchondral bone marrow edema and structural lesions (2–4).

Although MRI is especially capable of directly depicting bone marrow edema not detected with other imaging modalities, it is more time consuming and expensive than would be reasonable for routine use (5–7). Although conventional CT is generally regarded as a more reliable method with which to detect structural sacroiliac joint lesions, such as minute erosions, and although it is relatively affordable, highly available, and requires shorter examination times than MRI, it is not widely used because it cannot be used to assess bone marrow edema (2,8).

Dual-energy CT is an imaging technique that enables detection of traumatic bone marrow edema (9–14) and plasma cell infiltration of bone marrow (15,16) with high sensitivity and specificity if the patients were examined with a dual-energy mode. Dual-energy CT acquires two CT data sets at different energy levels simultaneously, and it can subsequently quantify and remove the individual chemical elements, like calcium, from those data sets. Postprocessing software is then used to remove calcium in trabecular bone by using the virtual noncalcium subtraction process, thus creating virtual noncalcium (VNCa) images (9–12). Increased water content (edema) or cellular components (multiple myeloma or bone metastases) in the bone marrow can be seen on VNCa images.

We hypothesized that dual-energy CT with visual analysis of color-coded images and quantitative region-of-interest (ROD)–based density measurements could enable detection of sacroiliac joint bone marrow edema in participants with axSpA, with precision comparable to that of MRI. Thus, the purpose of our study was to determine the diagnostic performance of a dual-energy CT VNCa technique in the detection and depiction of the
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The predefined tube current–time product was set at a ratio of 1.6:1 (tube A, 220 quality reference milliampere-seconds; tube B, 138 quality reference milliampere-seconds). Automated attenuation-based tube current modulation (CARE Dose 4D; Siemens Healthineers, Forchheim, Germany) was applied. The mean volume CT dose index of this protocol, according to our study participant protocol, was 7.4 mGy ± 2.6 (standard deviation) (range, 3.2–12.1 mGy), and the mean dose-length product was 121.0 mGy · cm (range, 62.3–438.6 mGy · cm). No intravenous contrast agent was used.

Image Reconstruction
By default, three different sets of images were acquired with each dual-energy CT scan: 80 kVp, Sn140 kVp, and weighted average (calculated from tube A and B data at a ratio of 0.3:0.7) to resemble the contrast properties of a 120-kVp standard CT image. For dual-energy–specific postprocessing data, axial sections of the 80- and Sn140-kVp data sets were reconstructed with a 1-mm section thickness (0.75-mm increment) by using a dedicated soft-tissue dual-energy kernel that included model-based iterative reconstruction (18).

Postprocessing Data from Dual-Energy CT Images
Postprocessing data from CT images was performed by using commercially available software (Syngo, via version VB 10B; Siemens Healthineers) with a three-material decomposition algorithm for bone mineral, yellow marrow, and red marrow (19,20). The relative contrast ratio was set to a value of 1.55 at 80 and Sn140 kV. The strength of the smoothing filter was set to three. The following material definitions were used for low and high kilovolt peak, respectively: red marrow, 57 and 55 HU; and yellow marrow, −106 and −87 HU for 90-kVp scans and −103 and −87 HU for 100-kVp scans (the manufacturer settings were slightly modified based on our own empirical experience) (21). VNCA images were displayed as color-coded overlay maps merged with weighted-average CT images in the postprocessing software application by using the bone marrow setting.

MRI Protocol
All MRI examinations were conducted at 3.0 T (Ingenia; Philips Medical Systems, Best, the Netherlands) by using a torso or abdomen coil. The MRI protocol included a fat-suppressed T2-weighted (repetition time msec/echo time msec, 2100–4000/100; echo train length, 15) fast spin-echo sequence in the oblique coronal and axial planes and a T1-weighted (410–500/10; echo train length, five) fast spin-echo sequence in the oblique coronal and axial planes, with a 3-mm section thickness, 0.3-mm intersection gap, 320 × 288 matrix, and 16 × 16 cm field of view.

Visual Image Analysis
Readers consisted of two staff radiologists (H.W. [reader 1], C.L. [reader 2]; 17 and 25 years of experience in musculoskeletal radiology, respectively), both of whom were blinded to MRI results and clinical information. Readers analyzed dual-energy CT images independently.

The maximum dimension of sacroiliac joints on oblique coronal VNCa CT images was selected, and the iliac surface...
of each sacroiliac joint was equally subdivided into three anatomic ranges. The axial position was also used as a reference or supplement to determine the extent of edema. A severity score depending on the extent of bone marrow edema in the affected area was assigned, as follows: grade 0, no edema; grade 1, mild edema (less than one-third of the sacroiliac joint was involved); grade 2, moderate edema (one-third to two-thirds of the sacroiliac joint was involved); and grade 3, severe edema (more than two-thirds of the sacroiliac joint was involved). This grading system is consistent with the definition of active sacroiliitis from The Assessment in Spondylo-Arthritis International Society/Outcome Measurements in Rheumatology Clinical Trials MRI scoring method (5). Sacroiliac bone marrow edema on MR images is also graded according to those recommendations (Figs 2–4). Readers were free to change window settings and magnification. In cases of interobserver disagreement, consensus ranking was obtained, and these results were used for further analysis. Only bone marrow lesions more than 2 mm from adjacent subchondral bone were included to minimize artifacts that might hamper accurate analysis of bone marrow in this zone (9,10).

MRI served as the reference standard. Edema was graded with the before-mentioned MRI scoring system. A third reader (X.H., 3 years of experience in musculoskeletal imaging) evaluated MR images for the presence of bone marrow edema. Reader 3 was blinded to the dual-energy CT results.

Quantitative Analysis of CT Numbers

After qualitative readings were completed, quantitative analysis was performed by readers 1 and 2 in consensus. MRI served as the reference standard to reconfirm the true range of edema. Readers independently measured the two sets of CT values. These were analyzed separately. Dual-energy CT numbers were obtained from VNCa images by using circular ROIs from the location in the edema zone marked as red under normal bone marrow green background on the color-coded images (Figs 2, 3), corresponding to high signal intensity on T2-weighted MR images. Up to five circular ROIs per study participant were placed on bone marrow edema zones on the color-coded images to obtain dual-energy VNCa CT numbers. In addition, five ROIs of 100 mm² or larger were randomly placed on the iliac surface of the contralateral sacroiliac joint or in areas of normal bone marrow (green) as seen on MR images to obtain CT data from healthy bone marrow.

Statistical Analysis

Interreader agreement for visual evaluation of dual-energy VNCa images was analyzed by using $\kappa$ statistics. A McNemar test was used to compare the difference between two readers in visual analysis of various extents of edema of sacroiliac joints. Sensitivity, specificity, accuracy, positive predictive value (PPV), and negative predictive value (NPV) were calculated on the basis of a contingency table with data from the qualitative visual analysis of dual-energy VNCa images. Study participants who received a diagnosis of bone marrow edema at MRI but in whom a diagnosis of edema was missed on VNCa images were considered to have false-negative findings. Participants in whom a diagnosis of edema was not made at MRI but in whom a misdiagnosis of bone marrow edema was made on VNCa images were considered to have false-positive findings.

Receiver operating characteristic (ROC) curve analysis and calculation of the area under the ROC curve were used to evaluate the CT numbers derived from dual-energy VNCa images. The interclass correlation coefficient was used to evaluate the interreader agreement of ROI-based CT numbers. Then, averaged CT numbers were compared with MR images by means of ROC analysis to determine the cutoff CT number showing the highest accuracy for presence or absence of bone marrow edema. From this cutoff value, sensitivity, specificity, accuracy, PPV, and NPV were calculated.

Continuous variables are reported as mean ± standard deviation. For comparison of dual-energy CT numbers among patients with severe, moderate, mild, or no edema, data were analyzed by using the Kruskal-Wallis test. In cases of statistical significance, further comparisons were performed by using the Mann-Whitney test.

A $P$ value of less than .05 was considered indicative of a significant difference. Statistical analyses were performed by using SPSS Statistics for Windows (version 21.0; IBM, Armonk, NY).

Results

There were 47 consecutive participants enrolled in this study (mean age, 27 years; age range, 14–41 years). There were 19 women (mean age, 29 years; age range, 17–41 years) and 28 men (mean age, 24 years; age range, 14–37 years). Study participant demographics and characteristics are outlined in Table 1.
Figure 2: Images in a 33-year-old man with left sacroiliitis of axial spondyloarthritis. Oblique coronal (a) fat-suppressed T2-weighted MR image and (b) gray-scale and (c) corresponding color-coded dual-energy virtual noncalcium CT images show moderate bone marrow edema (red) in the left ilium. In c, note the CT number of circular regions of interest (ROIs) in the bilateral ilium. The CT number of ROIs across the edematous area in the left ilium was 8 HU, and the CT number of the ROI across the nonedematous area in the contralateral ilium was −48 HU.

Figure 3: Images in a 33-year-old man with right sacroiliitis of axial spondyloarthritis. Oblique coronal (a) fat-suppressed T2-weighted MR image and (b) gray-scale and (c) corresponding color-coded dual-energy virtual noncalcium CT images show mild bone marrow edema (red) in the right ilium. In c, note the CT number of circular regions of interest (ROIs) in the bilateral ilium. The CT number of ROIs across the edematous area in the right ilium was −33 HU, and the CT number of ROIs across the nonedematous area in the contralateral ilium was −86 HU.

Figure 4: Images in a 27-year-old man with left sacroiliitis of axial spondyloarthritis. Oblique coronal (a) fat-suppressed T2-weighted MR, (b) gray-scale, and (c) corresponding color-coded dual-energy virtual noncalcium CT images show severe bone marrow edema (red) in the left ilium.

Dual-energy CT was performed within a mean of 4 hours (median, 3 hours; range 0.5–24.0 hours) after MRI. Forty-seven (89%) of the 53 study participants were available for final analysis, as they presented with at least one sacroiliac joint with bone marrow edema. Fifty-five (62%) of the 89 sacroiliac joints available for analysis were classified as having bone marrow edema at MRI. MRI was used to classify 34 sacroiliac joints as being free of edema, 24 as having mild bone marrow edema, 17 as having moderate bone marrow edema, and 14 as having severe bone marrow edema based on the extent of bone marrow edema in the ilium.

Visual Image Analysis
Interreader agreement for visual analysis of bone marrow edema was almost perfect (κ = 0.81). The McNemar test
results show that there is no statistical difference between readers 1 and 2 in visual analysis of edema in the sacroiliac joints (P = .167). Among the 53 study participants, readers disagreed as to whether bone marrow edema was present or absent at VNcCa CT on four joints in three patients.

For reader 1, 55 true-positive joints with bone marrow edema were found on MR images, seven of which were classified as having no edema on dual-energy VNcCa images. In addition, two participants who had no edema on MR images were identified as having bone marrow edema on dual-energy VNcCa images, and the results were classified as false-positive findings. For reader 2, four false-negative findings and three false-positive findings of bone marrow edema were found on dual-energy VNcCa images. For differentiation of bone marrow edema from no edema with dual-energy VNcCa CT, reader 1 achieved overall sensitivity of 87% (48 of 55), specificity of 94% (32 of 34), PPV of 90% (80 of 89), NPV of 96% (48 of 50), and accuracy of 82% (32 of 39); the respective values for reader 2 were 93% (51 of 55), 91% (31 of 34), 92% (82 of 89), 94% (51 of 54), and 89% (31 of 35) (Table 2).

Quantitative Analysis of Bone Marrow CT Numbers

Interobserver agreement for ROI-based CT numbers was excellent, with an interclass correlation coefficient of 0.97 (95% confidence interval [CI]: 0.91, 0.95) for severe bone marrow edema, 0.97 (95% CI: 0.91, 0.99) for moderate bone marrow edema, and 0.87 (95% CI: 0.70, 0.93) for mild bone marrow edema. The interclass correlation coefficient was 0.98 (95% CI: 0.92, 0.98) for no edema.

Mean CT numbers on VNcCa images of severe, moderate, mild, or no bone marrow edema are described in Table 3. There were gradual decreases of dual-energy VNcCa CT numbers from severe bone marrow edema to no edema for both readers. Significant differences in CT numbers on VNcCa images were also found in subjects with severe, moderate, mild, or no bone marrow edema (P < .001 for both readers) (Fig 5).

ROC analysis of dual-energy CT numbers in the differentiation of bone marrow edema from no edema revealed an area under the ROC curve of 0.93 (95% CI: 0.88, 0.98) for reader 1 and 0.91 (95% CI: 0.85, 0.97) for reader 2 (Fig 6, Table 4) (P < .001 for both readers). A cutoff value of −33 HU for reader 1 yielded overall sensitivity of 90% (49 of 55), specificity of 83% (28 of 34), and accuracy of 87% (77 of 89). Calculation of a cutoff value (−42 HU) for reader 2 resulted in an overall sensitivity of 94% (52 of 55), specificity of 80% (27 of 34), and accuracy of 87% (77 of 89).

Discussion

Our study results showed that the VNcCa technique of unenhanced dual-source CT scanning is feasible in the assessment of bone marrow edema in the sacroiliac joints of study participants with axSpA. Of note, we found visual analysis of dual-energy VNcCa images had a sensitivity of 87% and 93% (48 and 51
of 55 participants) and a specificity of 94% and 91% (32 and 31 of 34 participants) for readers 1 and 2, respectively. In addition, according to ROC analysis, the optimal cutoff value for discrimination between bone marrow edema and no edema in sacroiliac joints in study participants with axSpA was −33.4 HU for reader 1 and −42.35 HU for reader 2.

Dual-energy CT uses the energy dependence of the x-ray attenuation and allows for characterization and differentiation, especially of substances with a high atomic number (17,18). The use of a three-material decomposition model allows for the creation of VNCa images by subtracting calcium from CT data. To date, few studies have reported on the use of this technique to directly depict (a) trauma-associated bone marrow edema in the extremities (9,10) or spine (11–14,22,23) or (b) malignant bone marrow infiltration (15,16,24). However, to our knowledge, this is the first and largest prospective study to address the bone marrow edema associated with inflammatory rheumatic disorders when using dual-energy CT (25,26).

We systematically reported detection and identification of different ranges of bone marrow edema in the sacroiliac joints of study participants with axSpA using dual-source CT scanners and 80- and Sn140-kV tube voltages. These results are in keeping with those in the previous literature reporting 80- and 140-kV (tin filter) configuration in the detection of posttraumatic bone marrow edema in the ankle (10) and spine (11–14,22,23) or (b) malignant bone marrow infiltration (15,16,24). However, to our knowledge, this is the first and largest prospective study to address the bone marrow edema associated with inflammatory rheumatic disorders when using dual-energy CT (25,26).

We also reported detection and identification of different ranges of bone marrow edema in the sacroiliac joints of study participants with axSpA using dual-source CT scanners and 80- and Sn140-kV tube voltages. These results are in keeping with those in the previous literature reporting 80- and 140-kV (tin filter) configuration in the detection of posttraumatic bone marrow edema in the ankle (10) and spine (11–14,22,23) or (b) malignant bone marrow infiltration (15,16,24). However, to our knowledge, this is the first and largest prospective study to address the bone marrow edema associated with inflammatory rheumatic disorders when using dual-energy CT (25,26).

In our visual analysis, the results showed that VNCa images had sensitivity of 87% and 93% (48 and 51 of 55, respectively), specificity of 94% and 91% (32 and 31 of 34, respectively), accuracy of 90% and 92% (80 and 82 of 89, respectively), PPV of 96% (48 of 50) and 94% (51 of 54), and NPV of 82% (32 of 39) and 89% (31 of 35) for readers 1 and 2, respectively, with varying levels of clinical experience with the VNCa application. Diagnostic performance corresponded well to that reported in the literature for acute knee trauma (sensitivity, 86%; specificity, 95%) (9), acute ankle trauma (sensitivity, 90%; specificity, 81%; PPV, 25% or 27%; NPV, 99%) (10), and nondisplaced hip fractures (sensitivity range, 77%–91%; specificity range, 92%–99%) (23). Petritsch et al (22) reported sensitivity of 64.0%, specificity of 99.3%, accuracy of 93.9%, PPV of 94.1%, and NPV of 93.8% with use of a visual dual-energy VNCa image in the detection of traumatic bone marrow edema of vertebral bodies.

In our study, we observed seven false-negative and four false-positive findings for reader 1 and two false-negative and three false-positive findings for reader 2 at visual image interpretation. High PPVs (96% and 94%) in visual analysis indicate the potential role of dual-energy CT as a diagnostic tool in the diagnosis of bone marrow edema in sacroiliac joints. Moreover, excellent interobserver agreement for visual interpretation of color-coded VNCa images (κ = 0.81) substantiated the strong potential for using dual-energy CT clinically. However, there were seven and four false-negative findings at visual analysis of dual-energy CT. Possible reasons could be the varying levels of clinical experience with the VNCa application. Furthermore, identification of mild edema and no edema on VNCa images is sometimes variable between different readers.

In the quantitative analysis, the study by Wang et al (11) showed that the use of color-coded bone marrow images acquired with a dual-source scanner (100 and Sn140 kV) significantly improved sensitivity in the detection of bone marrow edema in patients with vertebral compression fractures. Promising values for sensitivity and specificity, 96.3% and 98.2%, respectively, in differentiating edematous from nonedematous vertebral bodies were reported for ROI-based attenuation measurements. Thus, the findings in our study are in good agreement with these data, as our observed sensitivity was 94% and our observed specificity reached 83% when we used ROC analysis to differentiate edematous from nonedematous sacroiliac joints. Furthermore, our results are similar to those of a previous study by Petritsch et al (22), which showed that ROC analysis of CT numbers achieved overall sensitivity of 92.0%, specificity of 82.6%, accuracy of 84.0%, PPV of 48.9%, and NPV of 98.3% in the differentiation of edematous vertebral bodies using a dual-source scanner (90 and Sn150 kV).

Our study also showed that the optimal cutoff value in our study population was −33.4 and −42.35 HU for readers 1 and 2, respectively. Bierry et al (13) found cutoff values for CT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reader 1</th>
<th>Reader 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (%)</td>
<td>87 (75, 94)</td>
<td>93 (82, 98)</td>
</tr>
<tr>
<td>Specificity (%)</td>
<td>94 (79, 99)</td>
<td>91 (75, 98)</td>
</tr>
<tr>
<td>Accuracy (%)</td>
<td>90 (77, 97)</td>
<td>92 (80, 99)</td>
</tr>
<tr>
<td>PPV (%)</td>
<td>96 (85, 99)</td>
<td>94 (84, 99)</td>
</tr>
<tr>
<td>NPV (%)</td>
<td>82 (66, 92)</td>
<td>89 (72, 96)</td>
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</table>

Note.—Data in parentheses are percentages. Data in parentheses are the sensitivity range, 77%–91%; specificity range, 92%–99% (23). Petritsch et al (22) reported sensitivity of 64.0%, specificity of 99.3%, accuracy of 93.9%, PPV of 94.1%, and NPV of 93.8% with use of a visual dual-energy VNCa image in the detection of traumatic bone marrow edema of vertebral bodies.

In our study, we observed seven false-negative and four false-positive findings for reader 1 and two false-negative and three false-positive findings for reader 2 at visual image interpretation. High PPVs (96% and 94%) in visual analysis indicate the potential role of dual-energy CT as a diagnostic tool in the diagnosis of bone marrow edema in sacroiliac joints. Moreover, excellent interobserver agreement for visual interpretation of color-coded VNCa images (κ = 0.81) substantiated the strong potential for using dual-energy CT clinically. However, there were seven and four false-negative findings at visual analysis of dual-energy CT. Possible reasons could be the varying levels of clinical experience with the VNCa application. Furthermore, identification of mild edema and no edema on VNCa images is sometimes variable between different readers.

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Our study also showed that the optimal cutoff value in our study population was −33.4 and −42.35 HU for readers 1 and 2, respectively. Bierry et al (13) found cutoff values for CT

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>No. of Participants or Joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>28 (60)</td>
</tr>
<tr>
<td>Female</td>
<td>19 (40)</td>
</tr>
<tr>
<td>Positive HLA-B27</td>
<td>38 (81)</td>
</tr>
<tr>
<td>Elevated C-reactive protein level</td>
<td>32 (68)</td>
</tr>
<tr>
<td>Subchondral bone marrow edema classified with MRI</td>
<td></td>
</tr>
<tr>
<td>No edema</td>
<td>34 (38)</td>
</tr>
<tr>
<td>Mild edema</td>
<td>24 (27)</td>
</tr>
<tr>
<td>Moderate edema</td>
<td>17 (19)</td>
</tr>
<tr>
<td>Severe edema</td>
<td>14 (16)</td>
</tr>
</tbody>
</table>

Note.—Data in parentheses are percentages and were calculated with a denominator of 47 patients or 89 joints. Mean age (P = .732) and participant sex distribution (P = .821) were not significantly different between the severe, moderate, mild, and no edema groups. HLA-B27 = human leukocyte antigen B27.
numbers with the highest sensitivity and specificity were 35 HU for thoracic vertebral bodies and 6.5 HU for lumbar vertebral bodies. Another study, however, showed the optimal cutoff value for both thoracic and lumbar vertebral bodies was -80 HU. The discrepancies in these observations could be explained by the use of different scanners, different kilovoltage settings, and different postprocessing algorithms (22). The present results also suggest that different parts of bones have different CT values. This hypothesis has also been confirmed by Guggenberger et al. (10), who showed that the optimal cutoff values to detect traumatic bone marrow edema of ankle mortise, talar dome, and talar body and head were -80, -70, and -39 HU, respectively.

Conventional CT generally has a short acquisition time, widespread availability, and a relatively low cost when compared with those of MRI. In addition, and more importantly, CT has been proved to be better than other imaging modalities, such as MRI and conventional radiography, particularly in the detection of structural damage, like minor structural erosion of sacroiliac joints in patients with axSpA (19). However, the inability of conventional single-energy CT to depict bone marrow edema, which is regarded as the early stage of active inflammation, significantly limits its clinical utility (15, 27). More recently, it has also been documented that dual-energy CT with the addition of color-coded VNCa images to standard CT images could significantly improve visual sensitivity of readers in the detection of bone marrow lesions, from 69.6% to 91.3% (16). Results from our study support the hypothesis that dual-energy CT with reconstruction of VNCa images has enabled both qualitative (visual) and quantitative analysis of bone marrow edema of sacroiliac joints in study participants with axSpA, with a precision comparable to that of MRI. We think it is clinically important to be able to simultaneously detect bone marrow edema and minor structural lesions in the sacroiliac joints of patients with axSpA.

Our study had some limitations. Our results should be interpreted with caution because of the relatively few participants included in this exploratory analysis. In addition, another inherent limitation of the VNCa algorithm is its inability to show mild bone marrow edema directly adjacent to cortical bone; this is due to incomplete masking of the cortex and spatial averaging. Mild bone marrow edema adjacent to cortical bone may be missed. Thus, the given diagnostic performance numbers may apply to clear and overt findings of sacroiliac joints at MRI but not to the rather large majority of patients with axSpA who show very subtle changes. Moreover, since dual-energy CT has two energy levels and often two x-ray sources, this may be a limitation when comparing different imaging modalities, such as MRI or conventional single-energy CT, used to assess the sacroiliac joints in patients with axSpA. However, our results show that the radiation dose administered to the patient is divided between two sources, resulting in dose neutrality when compared with conventional CT (28, 29). Finally, our results should be interpreted with caution because the performance measures obtained from ROC analysis tend to be overestimations because the same set of data were used to determine the cutoff values.

In conclusion, we observed excellent diagnostic performance of dual-energy CT with visual analysis of color-coded VNCa images and quantitative ROI-based density measurements in the detection of bone marrow edema and in the depiction of different ranges of bone marrow edema in sacroiliac joints of study participants with axSpA.

**Table 3: CT Numbers of Dual-Energy CT Virtual Noncalcium Images and for Different Ranges of Bone Marrow Edema for the Two Readers Separately**

<table>
<thead>
<tr>
<th>Characteristic and Statistic</th>
<th>Reader 1 (HU)</th>
<th>Reader 2 (HU)</th>
</tr>
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<tbody>
<tr>
<td>Severe</td>
<td>28 ± 5 (21–37)</td>
<td>28 ± 5 (22–38)</td>
</tr>
<tr>
<td>Moderate</td>
<td>4 ± 5 (-6 to 12)</td>
<td>4 ± 5 (-5 to 13)</td>
</tr>
<tr>
<td>Mild</td>
<td>-25 ± 12 (-47 to 7)</td>
<td>-23 ± 13 (-54 to 7)</td>
</tr>
<tr>
<td>No</td>
<td>-54 ± 20 (-88 to -21)</td>
<td>-55 ± 18 (-88 to -24)</td>
</tr>
</tbody>
</table>

*Note.—Unless otherwise indicated, data are mean CT number ± standard deviation and were derived from dual-energy virtual noncalcium images. Data in parentheses are the range. P values were calculated with the Kruskal-Wallis test. P < .05 indicates a significant difference.*

**Table 4: Diagnostic Performance of Dual-Energy Virtual Noncalcium Technique in Quantitative Analysis of Region of Interest-based Mean Attenuation Measurements**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reader 1</th>
<th>Reader 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (%)</td>
<td>89 (77, 96) [49/55]</td>
<td>95 (84, 99) [52/55]</td>
</tr>
<tr>
<td>Specificity (%)</td>
<td>83 (65, 93) [28/34]</td>
<td>79 (62, 91) [27/34]</td>
</tr>
<tr>
<td>Accuracy (%)</td>
<td>87 (75, 95) [77/89]</td>
<td>87 (75, 95) [77/89]</td>
</tr>
<tr>
<td>Area under the ROC curve</td>
<td>0.93 (0.88, 0.98)</td>
<td>0.91 (0.85, 0.97)</td>
</tr>
<tr>
<td>Cutoff value</td>
<td>-33.4</td>
<td>-42.35</td>
</tr>
<tr>
<td>P value</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

*Note.—Unless otherwise indicated, data are percentages. Data in parentheses are 95% confidence intervals, and data in brackets are numerators and denominators. Data are the results of comparison between edema and no edema. ROC = receiver operating characteristic.*

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