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Application of double-layer detector spectral CT calcicum supression technique in the diagnosis of traumatic bone marrow edema in the knee

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ABSTRACT

Objective: To investigate the accuracy of calcicum supression (CaSupp) technique derived from double-layer detector spectral computed tomography (DSCT) in the diagnosis of traumatic bone marrow edema in the knee.
Methods: Twenty-three patients with trauma in the knee who underwent DSCT and Magnetic Resonance Imaging (MRI) in the Third Hospital of Hebei Medical University from October 2021 to March 2022 were retrospectively collected. To make the evaluation more detailed and accurate, each knee was divided into 10 partitions. Bone marrow edema in each partition of the knee was evaluated by two physicians (physician A and B) using CaSupp images combined with conventional CT-CaSupp fusion false-color images. MRI results were used as the gold standard and the accuracy of the CaSupp technique was analyzed in the diagnosis of traumatic bone marrow edema in the knee. The CaSuppCT values of the normal bone marrow area and the bone marrow edema area were delineated, and receiver operating curve (ROC curve) was drawn to find the optimal cut-off value of CaSuppCT as the quantitative parameter for the diagnosis of bone marrow edema.
Results: The diagnostic sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) of physician A were 83.1 %, 98.1 %, 95.5 % and 92.1 %, respectively; those of physician B were 93.5 %, 97.4 %, 94.7 % and 96.8 %, respectively. The CaSuppCT values in the bone marrow edema areas were higher than those in the normal areas, and the difference was statistically significant. The area under the receiver operating characteristic curve (AUC) of the CaSuppCT values was 0.979, and the cut-off value was 7.05Hu*. The corresponding diagnostic sensitivity was 87.0 %, and specificity was 100.0 %.
Conclusion: The CaSupp technique derived from DSCT has high sensitivity and specificity in the detection of traumatic bone marrow edema in the knee, and can provide more imaging information for clinical practice.

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1. Introduction

Bone marrow edema of the knee caused by trauma is a common mechanical bone marrow edema, which is often accompanied by ligament injury. Bone marrow edema is observed in 80 % of patients with anterior cruciate ligament injury [1,2]. The existence of bone marrow edema is not only related to pain [3], but also has been found to be related to the damage of adjacent cartilage, affecting the subsequent healing process [4]. The early detection and identification of bone marrow edema plays an important role in determining the time point of clinical intervention, especially in the case of occult fracture [5]. Delayed treatment due to undetected bone marrow edema or occult fracture may result in nonunion, structural collapse, arthritis, osteonecrosis and other serious consequences. The main pathological changes of traumatic bone marrow edema are bone marrow hemorrhage, edema and trabecular microfracture [6]. Magnetic Resonance Imaging (MRI) is the most sensitive imaging method to detect and observe bone marrow edema [7]. However, compared with CT, MRI has its shortcomings of increased examination cost, longer time consumption and claustrophobic intolerance [8]. Traditional single-energy CT (SECT) could not observe bone marrow edema due to the mask of bone trabecular calcium tissue. The material separation technique of dual-energy CT (DECT) allows bone marrow edema to be observed by CT [9]. With the development of technology, DECT includes three types: high-low tube voltage switching single-source CT, dual-source CT and double-layer detector CT. Some studies have shown that high-low tube voltage switching single-source CT and dual-source CT have high sensitivity and specificity in the diagnosis of traumatic bone marrow edema in the knee [10]. The Calcicum Supression (CaSupp) technique derived from dual-layer detector spectral CT (DSCT) can inhibit calcium in bone to varying degrees and reduce the masking of bone trabecula on bone marrow edema, thus observing bone marrow edema [11]. In this study, MRI was taken as the gold standard to analyze the diagnostic accuracy of CaSupp technique of DSCT in traumatic bone marrow edema of the knee.

2. Patients and methods

2.1. Patients

This retrospective study was approved by the Ethics Committee of the Third Hospital of Hebei Medical University (Ethics No. 2021-102-1). All patient images and data used in the study have been consented. Patients with knee trauma admitted to the Third Hospital of Hebei Medical University from October 2021 to March 2022 were retrospectively collected. After trauma, the patient underwent DSCT to observe fracture, and MRI was performed to observe bone marrow edema, ligament, meniscus and surrounding soft tissue. Inclusion criteria: (1) post-traumatic bone marrow edema of knee was diagnosed by MRI; (2) the interval between DSCT and MRI was less than 2 weeks; (3) No history of surgery, tumor or infection in the knee; (4) No congenital or acquired deformity of the knee (including varus, valgus, femoral trochlear dysplasia, etc.)

2.2. DSCT protocol

All DSCT were obtained using the 128-slice double-layer detector spectral CT system (IQon; Philips Healthcare, Best, the Netherlands). The CT scanning parameters: tube voltage, 120 kVp with automatic attenuation dose modulation; rotation time, 0.4s; pitch, 0.984; collimator width, 64 $\times$ 0.625 mm; reconstruction layer thickness, 1.0 mm; and field of view (FOV), 18cm $\times$ 18 cm. Reconstruction was performed using the Philips ItelliSpace Portal workstation (Philips Healthcare, Best, the Netherlands). The operator (Y.Liu) imported the bone window data of spectral based imaging (SBI) with a thickness of 1.0 mm into the Spectral CT Viewer to generate the CaSupp image and the conventional CT-CaSupp fusion pseudo-color image. The pseudo-color type of red representing bone marrow edema was selected. Normal bone marrow is shown in green on the false-color image. The manufacturer's

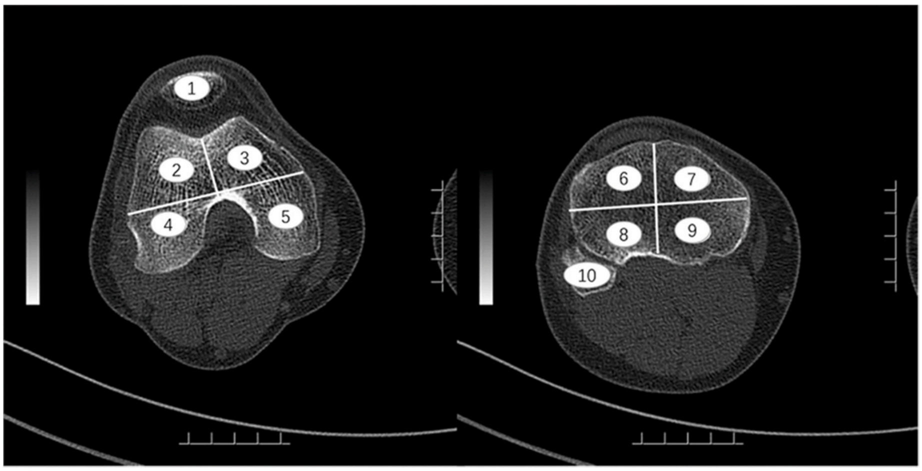

Fig. 1. Diagram of knee partitioning method.

recommended CaSupp index of 76.0 was used.

2.3. MRI protocol

MRI data were obtained using Philips Ingenia CX 3.0T (Philips Healthcare, Best, the Netherlands) and Siemens Verio 3.0T (Siemens Healthcare, Erlangen, Germany). The MRI protocol included proton density-weighted imaging with turbo inversion recovery magnitude (PD-STIR) in sagittal, coronal and transverse，and sagittal T1-weighted imaging (T1WI). The parameters of the PD-STIR were as follows: repetition time, 4000 ms; echo time, 30 ms or 25 ms; reverse Angle, 180°; layer thickness, 3.5 mm or 4.0 mm; FOV, 16cm × 16 cm or 18cm × 18 cm. The parameters of the sagittal T1WI were as follows：repetition time, 450 ms; echo time, 10 ms; reverse Angle, 150°; layer thickness, 4.0 mm; FOV, 18cm × 18 cm.

2.4. Image analysis

In the image analysis part, we artificially divided the knee into 10 partitions (Fig. 1). This method locates the bone marrow edema more accurately, and the consistency of DSCT with MRI results and the consistency of the two physicians' analysis results can be analyzed.

2.4.1. Subjective evaluation

Bone marrow edema was evaluated in both DSCT and MRI (0 = absence of bone marrow edema, 1 = presence of bone marrow edema). A physician (H.Yu) who has been engaged in osteomyographic diagnosis for more than 10 years determined the presence or absence of bone marrow edema in each partition of the knee based on MRI images. The diagnosis of bone marrow edema was based on flaky low signal on T1WI images and high signal on PD-STIR images (Fig. 4(A)).

Physician A (M.Wu) and Physician B (D.Jia) with more than 3 years of imaging experience determined the presence or absence of bone marrow edema in each partition of the knee based on CaSupp technique. The order in which the patient's images were viewed by two physicians was random. The two physicians can review all the data of DSCT at axial, coronal and sagittal levels, and give the diagnosis according to CaSupp (CaSupp images and conventional CT-Casupp fusion pseudo-color images). Both physicians are free to adjust all parameters related to the visualization of bone marrow edema. The diagnosis of bone marrow edema was characterized by flake density on CaSupp images (Fig. 4(Bi)) and red staining on conventional CT-Casupp fusion pseudo-color images (Fig. 4(Bii)). Any one of the image evaluators was blind to the results of the others.

2.4.2. Quantitative analysis

Quantitative measurements of CaSuppCT value in bone marrow edema areas and normal bone marrow areas were also performed by Physician A and Physician B. Circular areas of interest (ROI) were placed in areas of bone marrow edema and areas of normal bone marrow after two physicians determined the presence or absence of bone marrow edema in each partition. If bone marrow edema occurs to multiple partitions, the operators were required to select the one with the largest range to delineate the ROI. The distance between the edge of ROI and the bone cortex was > 2 mm, which was to reduce the interference of the bone cortex on the calcium inhibition. Finally, the average CaSuppCT value within the ROI was recorded. Physician A and Physician B quantified CaSuppCT values in bone marrow edema areas and normal bone marrow areas respectively according to the above procedure. The average of the values measured by the two physicians was used for data analysis.

3. Statistical analysis

Shapiro-Wilk test was used to evaluate the normality of CaSuppCT values in the bone marrow edema areas and the normal bone marrow areas. According to whether the data were normally distributed, the test method to analyze the difference between the two groups of data was selected. If the data were normally distributed, the *t*-test was used to analyze the difference between the two groups of data. If not, the Manne-Whitney test was used for analysis. Kappa test was used to evaluate the consistency of the subjective evaluation results of Physician A and Physician B. The diagnostic sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) of Physician A and Physician B were calculated. Receiver operating characteristic curve (ROC curve) was drawn to analyze the accuracy of CaSuppCT in the diagnosis of bone marrow edema and to find the cut-off value as a quantitative parameter. Statistical analysis of all data was performed using SPSS 24 (IBM SPSS Statistics, New York; USA).

4. Results

29 patients underwent DSCT in the Third Hospital of Hebei Medical University between October 2021 and March 2022 for knee trauma. Five of them were excluded due to lack of MRI images (4 MRI contraindications, 1 claustrophobia), and the other one due to incomplete MRI protocol. In the end, 23 patients were included in this study, including 17 males and 6 females, aged 38.22 ± 16.16 (range 14–72) years, and the time interval between trauma and DSCT was 6.91 ± 4.64 (range1–17) days. The interval between MRI and DSCT was 1.52 ± 2.61 (range1–10) days. The total Dose Length Product (DLP) of patients undergoing DSCT in this study cohort was 253.4 ± 53.7 (175.4–382.6) mGycm.

4.1. Subjective evaluation

MRI images showed bone marrow edema in 77 of 230 areas in the 23 knees. The results of the two physicians' assessment of bone marrow edema based on CaSupp technique were as follows: physician A identified 67 areas of bone marrow edema and physician B identified 76 (Table 1). In accordance with the results of MRI, the results of physician A included 3 false positive areas (2 in anterior lateral femur, 1 in posterior interior femur) and 13 false negative areas (3 in anterior lateral femur, 2 in anterior internal femur, 3 in posterior internal femur, 1 in posterior external femur, 1 in anterior internal tibia, 1 in posterior internal tibia, 1 in anterior external tibia, and 1 in fibula); the results of physician B included 4 false positive areas (2 in anterior lateral femur, 2 in anterior internal femur) and 5 false negative areas (1 in anterior lateral femur, 1 in anterior internal femur, 2 in posterior internal femur, and 1 in fibula). The Kappa value of consistency of bone marrow edema diagnosed by two physicians based on CaSupp technique was 0.828.

4.2. Quantitative analysis

The CaSuppCT values in the bone marrow edema areas and the normal bone marrow areas were shown in Fig. 2, and the values in the two groups were normally distribution (bone marrow edema areas: $W = 0.957$, $P = 0.408 > 0.05$; normal bone marrow areas: $W = 0.957$, $P = 0.413 > 0.05$), The ROC curve of CaSupp CT values for diagnosing bone marrow edema in the knee showed an area under the curve (AUC) of 0.979 and a cut-off value of 7.05Hu*, with a sensitivity of 87 % and a specificity of 100 % (Fig. 3).

5. Discussion

The appearance of DECT made CT image diagnosis a big step forward from anatomic imaging to functional imaging of substance recognition. DECT not only has the advantages of isotropic high-resolution, large gantry and fast scanning time [12], but also can conduct spectral imaging through the difference of material attenuation coefficient under different energy levels [9]. This study was to investigate the accuracy of CaSupp technique derived from DSCT in traumatic bone marrow edema of knee. The upper detector of DSCT uses the rare metal yttrium as the substrate of scintillation crystals, and the lower detector is composed of rare earth ceramic materials. Compared with high-low tube voltage switching single-source CT and dual-source CT, DSCT can realize simultaneous, homologous and co-direction scanning [13]. The simplicity of DSCT in clinical practice has led to its rapid popularity. The SBI can be automatically reconstructed by routine scan, without additional scanning time, providing more information for diagnosis.

In this study, patients with traumatic knee bone marrow edema were retrospectively collected, and CaSupp technique of DSCT was used to observe knee bone marrow edema, which finally obtained a high diagnostic efficacy. A number of published studies have evaluated the application of high-low tube voltage switching single source CT or dual source CT in the diagnosis of knee bone marrow edema, with reported sensitivities ranging from 87.1 % to 96.0 % and specificity ranging from 66.9 % to 97.6 % [3,10,14,15]. There were also studies on the application of CaSupp technique derived from DSCT in the diagnosis of bone marrow edema in other bone of human body, such as spine, wrist, etc. [11,13], all of which report high sensitivity and specificity, but no studies on the application of CaSupp technique derived from DSCT in the diagnosis of knee traumatic bone marrow edema have been reported. The knee partition method is used to evaluate the accuracy of CaSupp technique derived from DSCT in diagnosing bone marrow edema. The diagnostic accuracy of different partitions was counted, and the possible causes were analyzed. The results showed that the incidence of false negative and false positive in the distal femur was higher than that in other knee component bones. Bone is composed of cortical bone, trabecular bone, and red and yellow bone marrow filling between the trabecular bone. After acute trauma, bleeding, edema, microfracture of trabecular bone occur in the bone, resulting in increased interstitial fluid [16]. The CaSupp technique uses material decomposition to reduce the calcium content in bone and reduce the visible covering of bone trabecula on bone marrow edema, so that bone marrow edema can be observed. The observation of bone marrow edema by CaSupp technique also depends on the recognition of higher interstitial fluid content than normal bone marrow background. Therefore, bone marrow edema is more likely to be observed in the background of fatty yellow bone marrow. The composition of the bone marrow in the body changes with age [17,18]. Theoretically, with the increase of age, the hemorrhagic red bone marrow is gradually replaced by fatty yellow bone marrow, and this transformation occurs from periphery to center. The limb bones are the first to undergo the transformation, while the bone marrow of the central axis bone retains the hemorrhagic red bone marrow for a longer time. Therefore, the bone marrow composition of the femur and tibia is different, and the femur has a larger proportion of hemorrhagic red bone marrow than the tibia. Most of the patients in our collection were young people, and tibia may have a greater degree of bone marrow yelosis than femur, while femur still had a greater proportion of residual hemorrhagic red bone marrow. This may be the reason why the diagnostic accuracy of CaSupp technique in observing bone marrow edema in the distal femur with a larger proportion of hemorrhagic red bone marrow is not as good as that of other knee component bones. In addition, incomplete cortical masking and spatial averaging in adjacent cortical areas may also lead to false negative results [19].

In the study of quantitative parameters of CaSupp technique derived from DSCT, the cut-off value of CaSuppCT value in diagnosing

Table 1
Diagnostic accuracy of 2 physicians using CaSupp for knee bone marrow edema.

	True positive	False positive	True negative	False negative	Sensitivity	Specificity	PPV	NPV
Physician A	64	3	151	13	83.1 %	98.1 %	95.5 %	92.1 %
Physician B	72	4	150	5	93.5 %	97.4 %	94.7 %	96.8 %

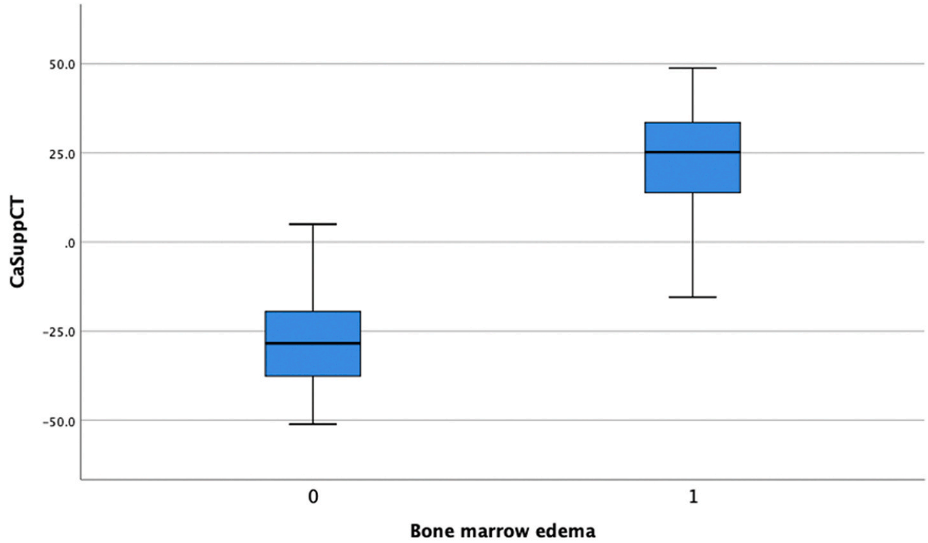

Fig. 2. The box chart shows CaSuppCT in the normal marrow area versus the marrow edema area.

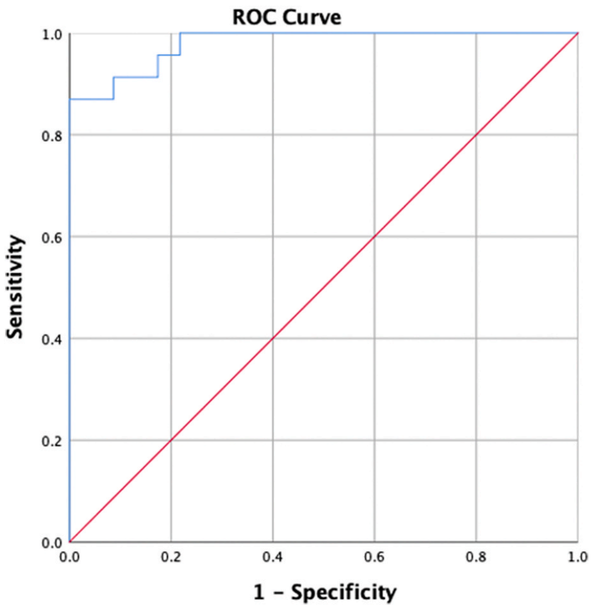

Fig. 3. ROC curve of diagnosis of knee bone marrow edema based on CasuppCT (AUC = 0.979).

knee bone marrow edema was 7.05Hu*. This value is affected by a number of factors, the most important of which is the change in the interstitial fluid. The higher than normal interstitial fluid content in the tissues of bone marrow edema is an important aspect of the visualization of bone marrow edema by CaSupp technique. This interstitial fluid content is affected by many factors, such as age, gender, injury type, bone site, amount of bleeding, and may even change with different nutritional status of the individual [20,21]. Therefore, the cut-off value of CaSuppCT value for the diagnosis of bone marrow edema in traumatic knee needs to be studied with larger data, wider population and more subgroups. This study also has its limitations. First of all, the sample size is small and the age span is large, so the representative characteristics cannot be obtained betterly. Secondly, the single CaSupp index recommended by the manufacturer was used in the study, and later studies with larger sample size, different ages, different trauma sites and different CaSupp indexes should be carried out.

In conclusion, the results show that the CaSupp technique derived from DSCT has a high accuracy in displaying traumatic knee bone marrow edema. The CaSupp technique can not only show the subtle condition of the bone cortex composed of the knee, but also the bone marrow edema, providing more image information for clinical practice.

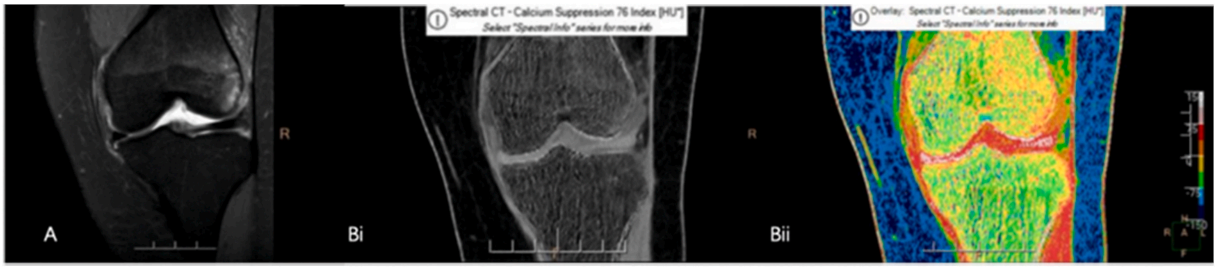

Fig. 4. Female, 14 years old, 10 days post-traumatic left knee.(A)The coronal proton-phase lipid-compression sequence of MRI manifested high signal in the lateral condyle of the left knee.B.Double-layer spectral CT CaSupp diagram (Bi) demonstrated patchy high density shadow in the corresponding area. Conversional CT-Casupp fusing pseudo-color image (Bii) showed that the corresponding area was different from the normal bone marrow staining showing flake red staining.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Mengfei Wu: Data curation, Investigation, Methodology, Writing – original draft. **Dezhao Jia:** Data curation, Validation, Writing - original draft. **Hong Yu:** Methodology, Validation. **Ying Liu:** Investigation. **Junfei Li:** Methodology. **Yongzhi Zhang:** Investigation, Software. **Shushan Dong:** Resources, Software. **Jian Zhao:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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