Original Investigation

Potential of Dual-Energy CT-Based Collagen Maps for the Assessment of Disk Degeneration in the Lumbar Spine

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Rationale and Objectives: Lumbar disk degeneration is a common condition contributing significantly to back pain. The objective of the study was to evaluate the potential of dual-energy CT (DECT)-derived collagen maps for the assessment of lumbar disk degeneration.

Patients and Methods: We conducted a retrospective analysis of 127 patients who underwent dual-source DECT and MRI of the lumbar spine between 07/2019 and 10/2022. The level of lumbar disk degeneration was categorized by three radiologists as follows: no/mild (Pfirrmann 1&2), moderate (Pfirrmann 3&4), and severe (Pfirrmann 5). Recall (sensitivity) and accuracy of DECT collagen maps were calculated. Intraclass correlation coefficient (ICC) was used to evaluate inter-reader reliability. Subjective evaluations were performed using 5-point Likert scales for diagnostic confidence and image quality.

Results: We evaluated a total of 762 intervertebral disks from 127 patients (median age, 69.7 (range, 23.0–93.7), female, 56). MRI identified 230 non/mildly degenerated disks (30.2%), 484 moderately degenerated disks (63.5%), and 48 severely degenerated disks (6.3%). DECT collagen maps yielded an overall accuracy of 85.5% (1955/2286). Recall (sensitivity) was 79.3% (547/690) for the detection of no/mild lumbar disk degeneration, 88.7% (1288/1452) for the detection of moderate disk degeneration, and 83.3% (120/144) for the detection of severe disk degeneration (ICC = 0.9). Subjective evaluations of DECT collagen maps showed high diagnostic confidence (median 4) and good image quality (median 4).

Conclusion: The use of DECT collagen maps to distinguish different stages of lumbar disk degeneration may have clinical significance in the early diagnosis of disk-related pathologies in patients with contraindications for MRI or in cases of unavailability of MRI.

Key Words: DECT; Computed tomography; Collagen Maps; Spine; Lumbar Disk Degeneration; Post-processing.

INTRODUCTION

Lumbar disk degeneration is a common and multifactorial condition contributing significantly to lower back pain and functional impairment (1). It is characterized by the gradual loss of intervertebral disk height, hydration, and structural integrity (2). Accurate evaluation of lumbar spine degeneration is crucial for guiding effective therapeutic interventions and improving patient outcomes (3). Currently, magnetic resonance imaging (MRI) is the modality of choice to evaluate lumbar disks (4), however, its

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limited availability in comparison to the more widely accessible computed tomography (CT) highlights the necessity of exploring alternative imaging approaches.

Over recent years, dual-energy CT (DECT) has emerged as a valuable imaging modality that allows material decomposition due to the possibility of analyzing energy attenuation behavior of tissues across different energy levels (5,6). There are several DECT-derived post-processing imaging methods that provide additional insights into tissue composition, including fat fraction analysis, iodine maps and collagen mapping (7,8). In the context of collagen maps, DECT post-processing provides spatially resolved information about the distribution of collagen by quantifying the heavy side-chains of hydroxyproline and hydroxylysine (7,9).

The diagnostic value of DECT-derived collagen mapping has been investigated for several musculoskeletal topics, in particular for ligamentous structures such as cruciate ligaments, tibiofibular syndesmosis and wrist ligaments (10–12). Two studies have investigated the diagnostic impact of DECT-derived collagen mapping for the evaluation of lumbar disk herniation (13,14), however, the degree of disk degeneration based on collagen maps has not yet been evaluated.

Intervertebral disks consist of an inner nucleus pulposus and an outer annulus fibrosus. Collagen is found in both components of the intervertebral disk; the annulus fibrosus possesses a higher collagen content, imparting strength to the disk, whereas the composition of the nucleus pulposus is more gel-like, with a higher concentration of water and proteoglycans (15). We hypothesized that DECT-derived color-coded collagen maps allow visualization of differences in the collagen content in intervertebral disks. Since the grading of lumbar disk degeneration is partly based on the loss of the differentiation between nucleus pulposus and annulus fibrosus (16), the purpose of our study was to investigate the diagnostic accuracy of DECT-derived color-coded collagen maps for the assessment of lumbar disk degeneration.

PATIENTS AND METHODS

Study Population

In this retrospective, single-center study, we reviewed our database for patients who underwent clinically indicated dual-source DECT and MRI of the lumbar spine between July 2019 and October 2022. Clinical indications encompassed suspected fractures, osseous lesions and diskoligamentous injuries of the lumbar spine. We included all patients with a maximum time interval of two weeks between DECT and MRI imaging to limit possible distortion of statistical correlation.

Exclusion criteria were: (I) patients with acute inflammatory process of the spine, (II) patients with osteosynthesis in the lumbar spine, (III) images with motion artifacts, (IV) patients with known malignancy of the spine.

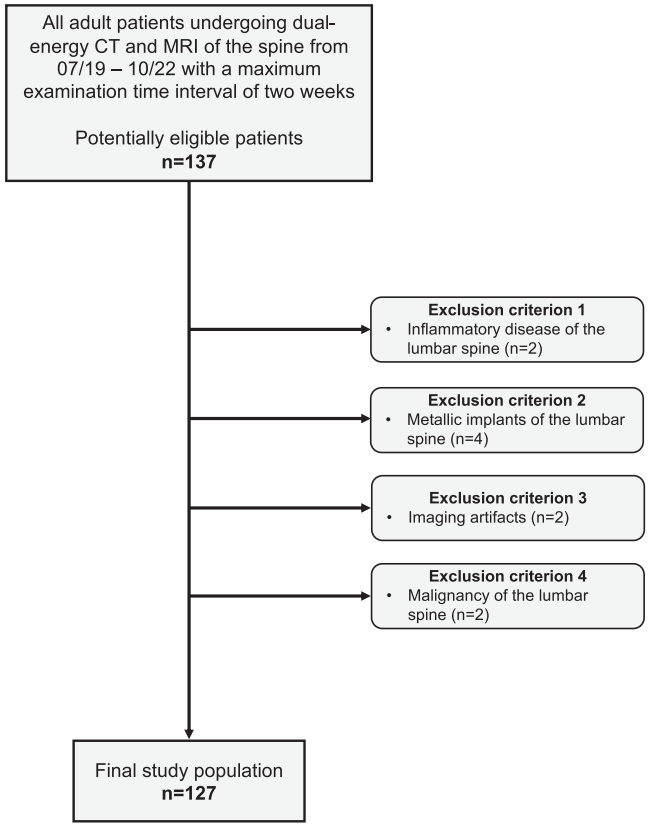

Figure 1. STARD flowchart of study inclusion.

Clinical data (date of birth, gender, clinical diagnosis) were collected from electronic medical records. All data were obtained in clinical routine. Figure 1 depicts the flowchart of patient inclusion according to Standards for Reporting Diagnostic Accuracy Studies (STARD).

Dual-Energy CT Acquisition Protocol, Image Reconstruction and Post-processing

All CT scans were performed on the same third generation dual-source DECT (Somatom Force; Siemens Healthineers) with the following default settings of the X-ray tubes: tube A: 90 kVp, 220 mAs; tube B: 150 kVp, 138 mAs; additional tin filter (Selective Photon Shield II, Siemens Healthineers). DECT image acquisition was performed in craniocaudal direction. Rotation time was 500 ms. Collimation was 128 × 0.6 mm. The applied protocol contained automatic attenuation-based tube current modulation (CARE Dose 4D; Siemens Healthineers). Mean volume CT dose index and mean dose-length product was recorded from the patient protocol. Three different image sets were acquired per each DECT scan: 90 kilovoltage peak (kVp), Sn150 kVp and weighted average (ratio, 0.5:0.5) to resemble contrast properties of a single-energy 120-kVp image. Postprocessing was performed on a commercially available syngo.via workstation (VB50, Siemens Healthineers, Munich, Germany). Color-coded collagen map reconstructions were performed using an

experimental algorithm with default settings as recommended by the vendor (application profile: knee; settings: collagen; public layout: fat map; width: 65, level: −30). DECT collagen maps were reconstructed with a slice thickness of 1 mm and increment of 0.75 mm in axial and sagittal plane. For image analysis, all image stacks were sent to the picture archiving and communication system (PACS, GE Healthcare, Germany).

Reference Standard (MRI)

Noncontrast MRI on a 3.0-T system (Magnetom PrismaFit; Siemens Healthineers) served as reference standard in all included patients. Standard T1-weighted spin-echo (repetition time msec/echo time msec, 650/10; matrix size, 288 × 384; section thickness, 4 mm; FoV read 260 mm), T2-weighted fast spin-echo (4000/89; matrix size, 358 × 448; section thickness, 4 mm; FoV read 260 mm), and turbo inversion-recovery magnitude (3500/39; matrix size, 388 × 384; section thickness, 4 mm; FoV read 260 mm) sequences were acquired in sagittal orientation.

DECT Image Analysis

Image evaluation was performed on a standard PACS workstation (Centricity, version 7.0; GE healthcare, Solingen, Germany).

To set the reference standard, two independent blinded board-certified radiologists (T.V. and I.Y.) with 36 and 7 years of experience in musculoskeletal imaging, respectively, performed reading of all MRI images. In case of disagreement, a third board-certified radiologist (J.-E.S.) with 10 years of experience evaluated the MRI scan and majority decision was reported in these cases. The level of degeneration in all lumbar intervertebral disks was categorized using the original Pfirrmann grading system (17). Pfirrmann Grade 1&2 was categorized as no/mild degeneration, Pfirrmann Grade 3&4 was categorized as moderate degeneration, and Pfirrmann Grade 5 was categorized as severe degeneration.

Three radiologists with different levels of experience in musculoskeletal imaging (reader 1, C.B., board-certified radiologist, 7 years of experience; reader 2, S.S.M., board-certified radiologist, 9 years of experience; reader 3, L.D.G., radiology resident, 4 years of experience) independently evaluated DECT-based collagen maps for the degree of lumbar disk degeneration after a brief introduction on the principles of DECT collagen maps and the Pfirrmann grading system. Analogous to the MRI rating, the DECT collagen map rating was based on the original Pfirrmann grading system, taking into account disk structure, distinction of nucleus pulposus and anulus fibrosus, signal intensity and height of the intervertebral disks. All three radiologists were blinded to the clinical records and CT reports.

The preset windows of the workstation could be freely modified for image analysis. Subjective evaluations were performed using 5-point Likert scales for diagnostic confidence (1 = insufficient, 2 = low, 3 = moderate, 4 = high, 5 = excellent) and image quality (1 =non-diagnostic, 2 =weak, 3 = moderate, 4 = good, 5 = excellent). Inter-reader reliability was evaluated using Intraclass correlation coefficient (ICC).

Statistical Analysis

Statistical analysis was performed using Stata (version 13, StataCorp, College Station, TX) and SPSS Statistics for MAC, version 29.0.1.0; IBM, Armonk, NY). Numeric values of continuous variables were reported as mean ± standard deviation. Categorial variables were expressed as percentages. The Kolmogorov–Smirnov test was used to assess normality of data distribution. Normally distributed values were analyzed with unpaired t-test. Wilcoxon Signed-Ranked test was used for data showing non-normal distribution.

Recall (sensitivity), precision, F1-score and accuracy of DECT-derived color-coded collagen maps were calculated with MRI as the reference standard for all examinations.

ICC was used in a two-way mixed-effects model to calculate interobserver agreement among all readers and was interpreted according to Koo/Li (18): ICC < 0.50 = poor agreement, ICC 0.50–0.75 = moderate agreement, ICC 0.75–0.90 = good agreement, ICC > 0.9 = excellent agreement.

A p-value (p) ≤ 0.05 indicated statistical significance.

Institutional Review Board Approval

The institutional ethic review board approved the present retrospective single-center study with a waiver for written informed consent.

RESULTS

We included a total of 762 lumbar intervertebral disks in 127 patients (median age, 69.7 (range, 23.0–93.7); female, 56). MRI identified 230 non/mildly degenerated disks (30.2%), 484 moderately degenerated disks (63.5%), and 48 severely degenerated disks (6.3%). Figure 2 visualizes the degree of lumbar disk degeneration across all evaluated lumbar disks.

The mean reconstruction time of collagen maps was 4 min (range, 3–5 min).

Baseline patient and clinical characteristics are summarized in Table 1.

Subjective Image Quality Per Intervertebral Disk

Subjective evaluation of the reference standard MRI revealed excellent diagnostic confidence for the evaluation of lumbar disk degeneration (median 5, interquartile range (IQR) 5–5), as well as excellent image quality (median 5, IQR 5–5).

Subjective evaluations of DECT-derived collagen maps showed high diagnostic confidence (median 4, IQR 3–4) and good image quality (median 4, IQR 3–4).

Inter-reader reliability for subjective evaluation in DECT collagen maps was good (image quality, ICC = 0.85 [95% CI, 0.80–0.89]; diagnostic confidence, ICC = 0.84 [95%

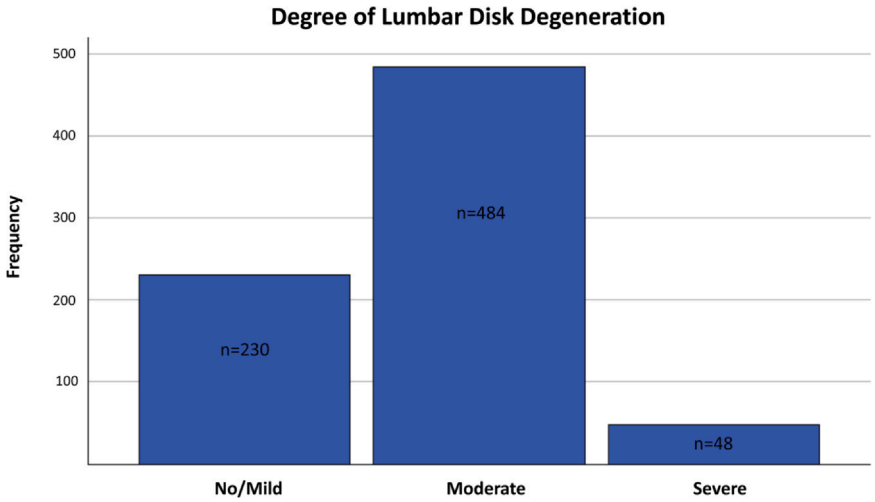

Figure 2. Bar chart of degree of lumbar disk degeneration across all evaluated lumbar disks. Level of disk degeneration was categorized using the Pfirrmann grading system. Pfirrmann Grade 1&2 was categorized as no/mild degeneration, Pfirrmann Grade 3&4 was categorized as moderate degeneration, and Pfirrmann Grade 5 was categorized as severe degeneration.

TABLE 1. Patient Characteristics

Parameters	Value
Number of patients (*n*)	127
Male/Female (*n*)	71/56
Age at date of MRI scan (median years, range)	69.7 (23.0–93.7)
Number of lumbar disks (*n*)	762
Degree of lumbar disk degeneration (*n*)	
Low (Pfirrmann 1&2)	230
Moderate (Pfirrmann 3&4)	484
Severe (Pfirrmann 5)	48

MRI, magnetic resonance imaging.

CI, 0.78–0.88]). Values of subjective analysis to assess lumbar disk degeneration across all readers are summarized in Table 2.

Overall Diagnostic Accuracy Per Intervertebral Disk

Overall image analysis of collagen maps revealed a recall (sensitivity) of 79.3% (547/690) for the detection of no/mild lumbar disk degeneration, 88.7% (1288/1452) for the detection of moderate disk degeneration, and 83.3% (120/144) for the detection of severe disk degeneration. Overall values for precision and F1-score were 80.3% and 79.8% for the detection of no/mild lumbar disk degeneration, 88.5% and 88.6% for the detection of moderate lumbar disk degeneration, and 80.0% and 81.6% for the detection of severe lumbar disk degeneration. Overall accuracy for collagen maps to evaluate lumbar disk degeneration was 85.5% (1955/2286). Interrater agreement for the ability to evaluate lumbar disk degeneration according to Pfirrmann was excellent for collagen maps (ICC = 0.9, 95% CI, 0.88–0.98).

TABLE 2. Subjective Analysis

Imaging Modality	Diagnostic Confidence	Image Quality
MRI (Reference Standard)	5	5
	(5–5)	(5–5)
Collagen Maps	4	4
All Raters	(3–4)	(3–4)
ICC	0.84 (95% CI, 0.78-0.88)	0.85 (95% CI, 0.80–0.89)
Collagen Maps	4	4
Rater 1	(3–4)	(3–4)
Collagen Maps	4	4
Rater 2	(3–4)	(3–4)
Collagen Maps	4	4
Rater 3	(3–4)	(3–4)

Values of subjective analysis to assess lumbar disk degeneration. Subjective evaluations were performed using 5-point Likert scales for diagnostic confidence (1 =insufficient, 2 =low, 3 =moderate, 4 =high, 5 =excellent) and image quality (1 =non-diagnostic, 2 =weak, 3 =moderate, 4 =good, 5 =excellent). CI, confidence interval; ICC, Intraclass correlation coefficient; MRI, magnetic resonance imaging.

When comparing the results of each CT reader, the accuracy was highest among the most experienced reader (rater 2, accuracy 88.0% [670/762] and lowest among the least experienced reader (rater 3, accuracy 83.3% [635/762]).

In detail, reader 1 achieved a sensitivity of 83.5% (192/230) to detect no/mild disk degeneration, a sensitivity of 85.3% (413/484) to detect moderate disk degeneration, and a sensitivity of 93.8% (45/48) to detect severe disk degeneration.

Reader 2 achieved sensitivity values of 74.8% (172/230) for no/mild disk degeneration, 94.2% (456/484) for moderate disk degeneration, and 87.5% (42/48) for severe disk degeneration. The least experienced reader (reader 3) achieved a sensitivity of 79.6% (183/230) to detect no/mild disk degeneration, a sensitivity of 86.6% (419/484) to detect moderate disk degeneration, and a sensitivity of 68.8% (33/48) to detect severe disk degeneration.

Values of diagnostic accuracy for DECT-derived color-coded collagen maps are summarized in Table 3.

Figure 3 demonstrates a case example of a 32-year-old female patient who received a CT and MRI of the lumbar spine following trauma. Figure 4 illustrates examples of DECT-derived collagen maps across different stages of disk degeneration.

DISCUSSION

In this study, we aimed to investigate the diagnostic utility of DECT-derived color-coded collagen maps in assessing lumbar disk degeneration. The key message emerging from our findings suggests that DECT-derived collagen maps may represent a valuable tool for the evaluation of lumbar disk degeneration. To our knowledge, this is the first study that investigates this algorithm in disk degeneration of the spine.

Our results revealed promising diagnostic accuracy for DECT-derived collagen maps in distinguishing different stages of lumbar disk degeneration. The overall accuracy of the DECT-derived collagen maps, indicative of the ability to detect various degrees of degeneration, was substantial with an accuracy of 85.5%. The high inter-reader agreement further supports the reliability of DECT-derived collagen mapping in assessing lumbar disk pathology (ICC = 0.9).

Globally, lumbar disk degeneration is a significant contributor to lower back pain (19–22). Degenerative changes in intervertebral disks can result in mechanical stress on surrounding structures, nerve compression, and inflammation, leading to pain and discomfort (23,24). Currently, MRI is considered the gold standard for assessing intervertebral disks and diskoligamentous injuries of the spine in general (25). However, there are several DECT-derived algorithms that allow for additional insights into tissue composition via post-processing material decomposition (26,27). These techniques have been extensively investigated in the context of spine pathologies. For example, in the context of bone marrow edema in incidental vertebral fractures of the spine, the impact of DECT-derived color-coded VNCa reconstruction has already been validated (28). In their study from 2018, the authors demonstrated that DECT-derived VNCa reconstructions substantially improve the characterization of incidental compression fractures of the spine in staging CTs by allowing visualization of bone marrow edema with AUC values of 0.98.

The potential of DECT-derived VNCa reconstruction has also been evaluated for pathologies of intervertebral disks in

TABLE 3. Diagnostic Accuracy of Collagen Maps for the Assessment of Lumbar Disk Degeneration

Diagnostic Accuracy Collagen Maps	Recall (Sensitivity)			Precision			F1-Score		
Lumbar disk degeneration	No/mild	Moderate	Severe	No/mild	Moderate	Severe	No/mild	Moderate	Severe
Collagen Maps Overall	79.3% 547/690	88.7% 1288/1452	83.3% 120/144	80.3%	88.5%	80.0%	79.8%	88.6%	81.6%
ICC	0.9 (95% CI, 0.88–0.98)								
Collagen Maps Rater 1	83.5% 192/230	85.3% 413/484	93.8% 45/48	76.2%	91.0%	80.4%	80.0%	88.1%	86.5%
Collagen Maps Rater 2	74.8% 172/230	94.2% 456/484	87.5% 42/48	91.0%	87.7%	79.2%	82.1%	90.8%	83.1%
Collagen Maps Rater 3	79.6% 183/230	86.6% 419/484	68.8% 33/48	76.3%	87.1%	80.5%	77.9%	86.8%	74.1%

Values of objective analysis to assess lumbar disk degeneration including recall (sensitivity), precision, and F1-score across all readers. CI, confidence interval; ICC, Intraclass correlation coefficient; MRI, magnetic resonance imaging

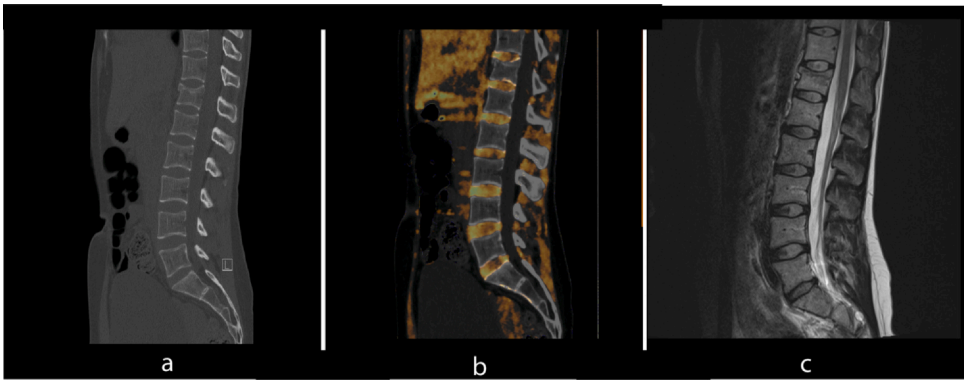

Figure 3. Sagittal reconstructions of gray-scale CT (**a**), collagen maps (**b**) and T2-weighted MRI (**c**) of the lumbar spine. This 32-year-old female patient has been referred to the emergency department with lumbar back pain after a car accident. The subsequent performed DECT revealed a compression fracture of TH12. Subsequently, a lumbar spine MRI was performed to rule out diskoligamentous injuries and further fractures. Sagittal reconstructions of DECT-derived collagen maps (**b**) visualize the collagen content of the lumbar disks, with higher signal in the anulus pulposus when compared to the nucleus pulposus.

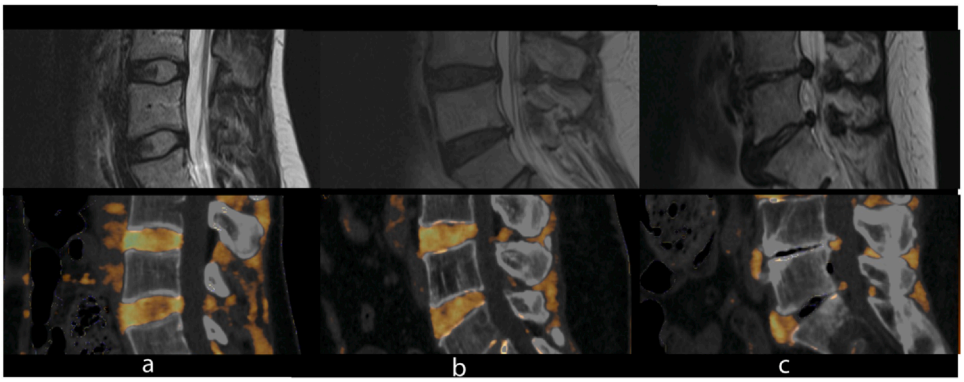

Figure 4. Sagittal reconstructions of T2-weighted MRI (upper row) and DECT collagen maps (lower row) of the lumbar spine across different stages of lumbar disk degeneration. (**a**) illustrates two non/mildly degenerated disks, (**b**) illustrates two moderately degenerated disks, and (**c**) illustrates two severely degenerated disks.

particular. To be more precise, several studies have demonstrated the ability of VNCa reconstructions to evaluate disk herniation in the lumbar and thoracic spine. In their study from 2019, the authors could confirm higher sensitivity and specificity for the assessment of lumbar disk herniation (sensitivity 91%, specificity 92%) compared to standard gray-scale CT (sensitivity 80%, specificity 85%) (29). Similar findings were confirmed in a study from 2021 for the assessment of thoracic disk herniation (sensitivity 94%, specificity 96%) (30).

Recently, an innovative DECT-derived collagen algorithm has been introduced, enhancing the capability to visualize and analyze collagen distribution within tissues through the application of DECT technology (7). The presence of collagen in intervertebral disks underscores the potential diagnostic impact of DECT-derived collagen maps for the assessment of intervertebral disks. The value of DECT-derived collagen maps for the evaluation of intervertebral disks has already been evaluated in a recent study from 2023 (14). In their retrospective study, the authors evaluated the diagnostic impact of DECT-derived collagen maps for the detection of lumbar disk extrusion and sequestration. Analyzing patients with acute low back pain, the authors demonstrated higher diagnostic accuracy values for combined DECT collagen maps and standard CT compared to standard CT alone (sensitivity 96.6% vs. 87.2%, specificity 99% vs. 95.4%, and diagnostic accuracy 98.7% vs. 94.5%). It is noteworthy that the study did not include patients with disk protrusion. Investigating this subgroup would be intriguing, given that disk protrusion cases are more prevalent than extrusion and sequestration cases (31,32). Another study from 2021 also evaluated the ability of DECT collagen maps for the assessment of lumbar disk displacement, however, the small study population ($n = 13$ patients) limits the generalizability of this study.

Whereas the ability of DECT collagen maps to evaluate disk herniation has been investigated in these two studies, the

diagnostic accuracy of DECT collagen maps for the assessment of disk degeneration has not yet been evaluated. Taken together, our results further approve the potential to assess intervertebral disk morphology in CT by confirming the value of DECT-derived color coded maps for the assessment of lumbar disk degeneration.

While our study provides promising insights into DECT post-processing, it is not without limitations. The retrospective nature and single-center design may introduce biases, and further multi-center studies with larger and more diverse cohorts are warranted to validate our findings. Also, in addition to the evaluation of lumbar disk degeneration, further studies could investigate the impact of DECT collagen maps for the differentiation of cervical and thoracic disk degeneration.

Second, our exclusion criteria, such as known malignancy or acute inflammatory processes, might inadvertently exclude certain subgroups relevant to lumbar disk degeneration. This potential selection bias might limit the generalizability of our findings. Last, the DECT-derived color-coded collagen reconstruction algorithm that is used in our study is vendor-specific. Consecutively, the technical approach requires the dual-source DECT system, which limits the transferability of our results to imaging departments that provide this scanner.

In conclusion, this is the first study suggesting DECT-based color-coded collagen maps as an additional tool for the classification of lumbar disk degeneration. The algorithm provides spatially resolved information about the distribution of collagen and allows visualization and differentiation of collagen content within intervertebral disks. MRI is the current modality of choice for evaluating lumbar disks, but its accessibility limitations pose challenges, particularly in certain patient populations or clinical settings. Therefore, the use of DECT-derived collagen maps to distinguish different stages of lumbar disk degeneration may have clinical significance in the early diagnosis of disk-related pathologies. This may be especially relevant in cases of unavailability of MRI and in patients with contraindications for MRI, such as patients with claustrophobia and patients with non-MRI-compatible devices.

GUARANTOR

The scientific guarantor of this publication is Prof. Dr. Thomas J. Vogl.

INFORMED CONSENT

Written informed consent was waived by the Institutional Review Board.

ETHICAL APPROVAL

Institutional Review Board approval was obtained.

METHODOLOGY

Methodology:

- retrospective

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DECLARATION OF COMPETING INTEREST

The authors of this manuscript declare relationships with the following companies:

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