IJMS

Original Article

Ultra-Low Dose Computed Tomography Imaging in Quantifying Bone Trauma and Disorders: A Cross-Sectional Study

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Received: 16 March 2024
Revised: 10 June 2024
Accepted: 12 July 2024

What's Known

- Conventional computed tomography uses a huge number of projections taken from 360-degree angles around the patient to reconstruct each slice, then it can detect abnormal and normal details of the bone structures.
- Radiation dose to the patient is quite high in conventional computed tomography protocols. It increases the risk of cancer.

What's New

- Ultra-low-dose computed tomography protocol with 98% dose reduction, compared to conventional computed tomography, can be used to detect extremity and spine bone fractures.
- The quality of extremity and spine bone computed tomography images produced by ultra-low dose computed tomography protocol with Iterative Model Reconstruction level 2 is acceptable diagnostically.

Abstract

Background: X-ray computed tomography (CT) is a standard tool for diagnosing bone abnormalities. CT dose optimization is strongly recommended, due to the stochastic effects of x-ray. This study aims to assess the effectiveness of ultra-low-dose CT (ULD-CT) imaging, reconstructed using an Iterative Reconstruction (IR) algorithm, in detecting bone trauma and disorders.

Methods: In the present cross-sectional study, 71 patients with CT requests for spine or extremity (limb) bone underwent scanning using standard dose (SD) and ULD-CT protocols, in Shahid Faghihi Hospital, Shiraz, Iran from June 2019 to June 2020. The SD and ULD-CT protocols used 120 kVp and 80 kVp, respectively. The CT images were reconstructed using the standard and IR algorithms. CT dose indices, including the volume CT dose index ($CTDI_{vol}$), dose-length product (DLP), and effective dose (ED), were employed. To assess image quality, a five-point scoring system was used. The sensitivity and specificity of the ULD-CT images were calculated.

Results: The findings indicated that ULD-CT images accurately identified 113 out of 118 bone trauma and disorders. The quality of ULD-CT images received "very good", "good" and "acceptable" scores for both spine and extremity (limb) bones. The sensitivity and specificity of ULD-CT images for bone trauma and disorders were 67%–95% and 100%, respectively, with about a 98% dose reduction.

Conclusion: The ULD-CT protocol for bone imaging achieved a remarkable dose reduction, while the image quality was reported as acceptable. Consequently, ULD-CT images reconstructed using an IR are suitable and can be tuned further in the future for acceptable use in patients with bone trauma and disorders.

Please cite this article as: Zarei F, Ahmadi SM, Dehbani-Zadeh S, Jafari A, Akondi V, Chatterjee S, Mirhosseini SAR, Ravanfar Haghighi R. Ultra-Low Dose Computed Tomography Imaging in Quantifying Bone Trauma and Disorders: A Cross-Sectional Study. Iran J Med Sci. doi: 10.30476/ijms.2024.102043.3477.

Keywords ● Tomography, X-ray computed ● Bone diseases ● Computed tomography, multidetector

Introduction

Bone fractures are common in the Emergency Department (ED), so plain radiography is the initial choice for finding a possible fracture due to being cost-effective and easily assessed. On the other hand, radiography is technique-dependent, and it does not have enough quality to diagnose the certain fracture, due to the overlapping of tissues.[1] Plain radiography does not allow the detection of detailed features, which is essential for the early treatment of bone disorders such as bone fractures.[2-6] Early detection of fractures can impact the outcome of treatment and complications.[7] This limitation can be addressed through computed tomography (CT), which produces a very accurate diagnosis of fractures.[8-13]

In the 1970s, after the invention of CT, orthopedic surgeons started to characterize fractures by using CT instead of conventional radiography.[14] However, compared with plain radiography, the patient dose in CT is significantly higher. On the other hand, CT image contrast is much higher than that given by radiography.

Inevitably, a portion of the radiation is absorbed by the patient's body, which can increase the risk of stochastic effects such as carcinogenesis and genetic disorders.[15-20] Therefore, the CT is only recommended for selected patients (justification).[9, 21] To improve its usage, it is critical to optimize the radiation dose. Achieving the right balance between radiation dose reduction and image quality is a primary goal of modern CT machines. Reduction of the tube current (mAs) and the voltage (kVp) applied to the X-ray tube have a substantial impact on reducing the number of X-ray photons.[22, 23] Consequently, this minimizes radiation exposure to the patient. However, it is essential to note that as the number of photons decreases, there is an increase in image noise, which, in turn, leads to a decrease in image contrast and overall image quality.[24-26] Since extremities (limbs) and spines are made of bone, which has a larger effective atomic number than soft tissues surrounding the bone, a reduction of voltage (kVp) improves the contrast.[27-29] This advantage is accompanied by a disadvantage in that as the photon number decreases, it gives rise to higher noise.

On the other hand, modern CT systems employ iterative reconstruction (IR) algorithms that can compensate for the noise due to reduced photon numbers (patient dose) while maintaining image quality in the ultra-low dose (ULD) CT protocol.[30] Researchers have shown that ULD-CT images can be used in acute circumferential skeleton and ankle fractures as an alternative method for plain X-ray radiography.[7, 31]

The primary objective of this study is to assess the efficacy of ULD-CT images in detecting bone trauma and disorders. This investigation focuses on evaluating the sensitivity and specificity of ULD-CT bone images, with standard-dose CT images serving as the reference standard.

Patients and Methods

This cross-sectional study was approved by the ethical committee of the Shiraz University of Medical Sciences, with IR.SUMS.MED.REC.1398.333 as the approval code. This study was conducted on 71 patients with bone complications, such as trauma (e.g., fracture), disorders (e.g., degenerative joint disease or DJD), and extremity (limb) and spine problems, who had been referred to the CT department of Shahid Faghihi Hospital affiliated with the Shiraz University of Medical Sciences, Iran. The patients being referred to the CT department with bone trauma history and disorders, and those who accepted to sign the consent form for scanning with the Ultra-Low Dose CT (ULD-CT) protocol after scanning with the standard-dose CT (SD-CT) protocol, were recruited (inclusion criteria) in the study. The exclusion criteria were fixation devices on bone, pregnancy, and the patients who were reluctant to participate.

It has to be mentioned that six patients out of 71 had metallic devices or prostheses and were excluded from this study.

Philips Ingenuity 128-slice CT scanner (Philips Health Care, Cleveland, OH, USA) was used to scan patients in this study. Standard dose CT protocol used 120 kVp or 100 kVp (for wrist), automatic tube current modulation (mAs), and CT images were reconstructed by iDose-Level 3, a hybrid iterative reconstruction algorithm (Philips Healthcare, Cleveland, OH, USA). While the ULD-CT protocol used 80 kVp, 15 mAs were fixed, and IMR level 2 (Iterative Model Reconstruction, Philips Healthcare, Cleveland, OH, USA) was used for the reconstruction algorithm. The rest of the parameters, such as slice thicknesses, rotation time, pitch factor, and others, were similar in both standard and ULD CT protocols. CT dose indices such as CT dose index volume ($CTDI_{vol}$), in mGy, and Dose-Length Product (DLP), in mGy.cm, were extracted from the page of the dose report available at the end of each CT series. DLP values were used to approximate the Effective Dose (ED) in mSv by multiplying the conversion coefficient (in mSv/mGy.cm).[32]

The image quality of bone ULD-CT images was evaluated independently by two radiologists with more than 10 years of experience. The findings of ULD-CT of bone were categorized into normal, fracture-displacement, degenerative joint changes, lytic or sclerotic lesions, soft tissue disorders, and chronic bone changes (including bone sclerosis, osteopenia, and so on). The quality of ULD-CT bone images was graded by the 5-scale scoring system based on the image noise and its interference with diagnostic image quality, as illustrated in table 1.

It has to be mentioned that the two radiologists were blind to the diagnostic findings of the corresponding standard dose CT images and also to each other's findings.

The sensitivity and specificity of the bone ULD-CT images were calculated by considering the standard dose of bone CT images as a gold standard protocol. The ability of the ULD-CT to detect bone trauma and disorders to the total number of cases detected by the standard dose CT (gold standard), presented the sensitivity. Moreover, the number of normal bone structures detected by ULD-CT to the total population of normal bone cases detected by the standard dose CT protocol determined the specificity of the ULD-CT protocol.[33] The sensitivity and specificity of the present study were calculated by Statistical Package for the Social Sciences (SPSS, IBM Corp. Armonk, NY, USA) version 26.

Results

The results from demographic data analysis showed that out of 65 patients, 34 (52%) were male and 31 were female (48%), with a mean age of 42 years (between 12 and 78 years).

The type and frequency of bone CT images taken in the present study were divided into two sections, anatomically: (1) the CT images of limbs or extremities consisted of 35 cases, and (2) the CT images of spines included 30 cases. All the results that are presented correspond to the data obtained on discarding the six cases having metallic devices as is mentioned in the materials and methods section. We excluded these six cases after taking the CT images because we found the images to be of very poor quality in both standard dose and ULD-CT.

The estimated effective dose (ED in mSv) for different bones in standard and ULD-CT protocols were calculated and are shown in table 2. It can be seen from table 2 that the lumbosacral (LS) spine has the maximum effective dose in both standard (6.8 mSv) and ultra-low dose (0.17 mSv) CT protocols. Additionally, in extremity (limb) bone CT images, the maximum effective dose for both protocols, effective doses of standard and ULD-CT protocols are 8.6 mSv and 0.1 mSv, corresponding to the shoulder. Furthermore, it is seen from table 2 that the maximum effective dose reduction by using the ULD-CT protocol occurred for shoulder (about 99% dose reduction) CT images, followed successively by the spine (about 98% dose reduction), compared to the standard dose. On the other hand, the lowest dose reduction (87%), in using the ULD-CT protocol, belongs to the CT image of the wrist, as was expected.

The result of the frequency distribution of image quality analysis demonstrated that the quality of the bone CT images taken by the standard dose protocol was reported as very good in 59 cases (91.5%) and good in six cases (8.5%). The quality of the bone CT images captured by the ULD-CT protocol was reported as very good quality in 15 cases (22.5%), good quality in 24 cases (36.6%), and medium or acceptable quality, in 20 cases (31%). While the radiologist's reports show that none of the bone CT images taken by the standard dose protocol

Table 1: Scoring system of imaging quality assessment

Score	Category	Description
0	Very bad	Extreme noise, which is not suitable for diagnostic imaging
1	Bad	High noise, which interferes with diagnostic imaging
2	Acceptable or medium	Moderate noise, which does not interfere with acceptable diagnostic imaging
3	Good	Low noise
4	Very good	Without noise or negligible noise

Table 2: The estimated effective dose (in mSv) for spine and extremity (limb) bones in standard and ULD-CT protocols

dy parts		Mean effective dose (mSv) in Standard dose protocol	Mean effective dose (mSv) in Ultra-Low Dose protocol	Dose reduction Factor (%)
Spine	Cervical	2.08	0.04	98
	Thoracic	5.9	0.14	98
	lumbosacral	6.8	0.17	97
Extremity (Limb)	Shoulder	8.6	0.1	99
	Elbow	0.07	0.006	91
	Wrist	0.03	0.004	87
	Hip	5.17	0.114	98
	Leg	0.08	0.006	93
	Knee	0.06	0.004	93
	Ankle	0.03	0.001	97
	Foot	0.01	0.001	90

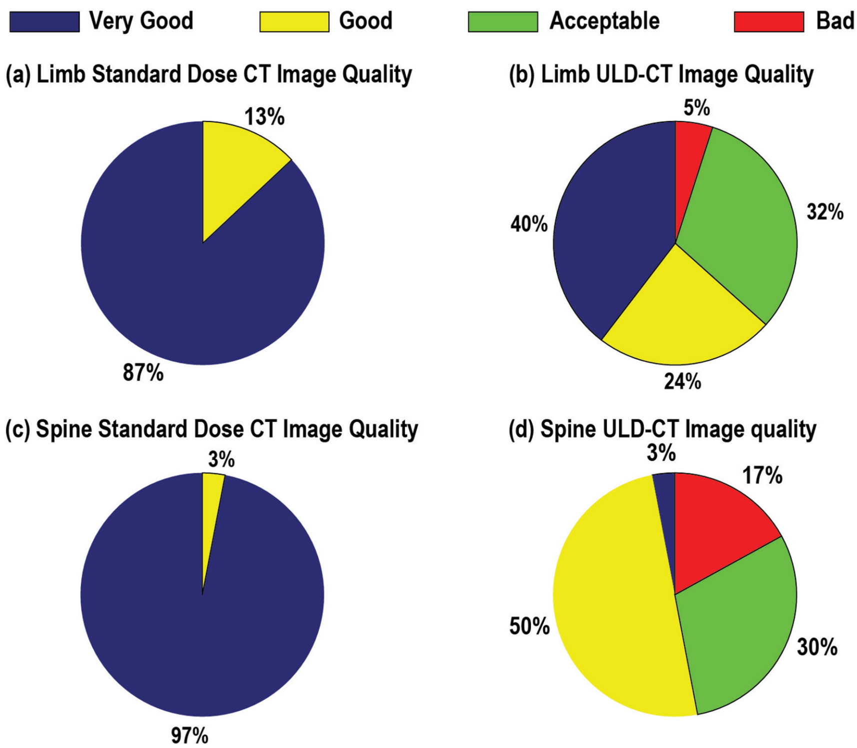

Figure 1: Pie chart Frequency distribution of bone CT image quality is shown in the scan regions, (a and b): extremities (limbs), and (c and d): spine, for standard dose and Ultra-Low dose Computed Tomography (ULD-CT) protocols.

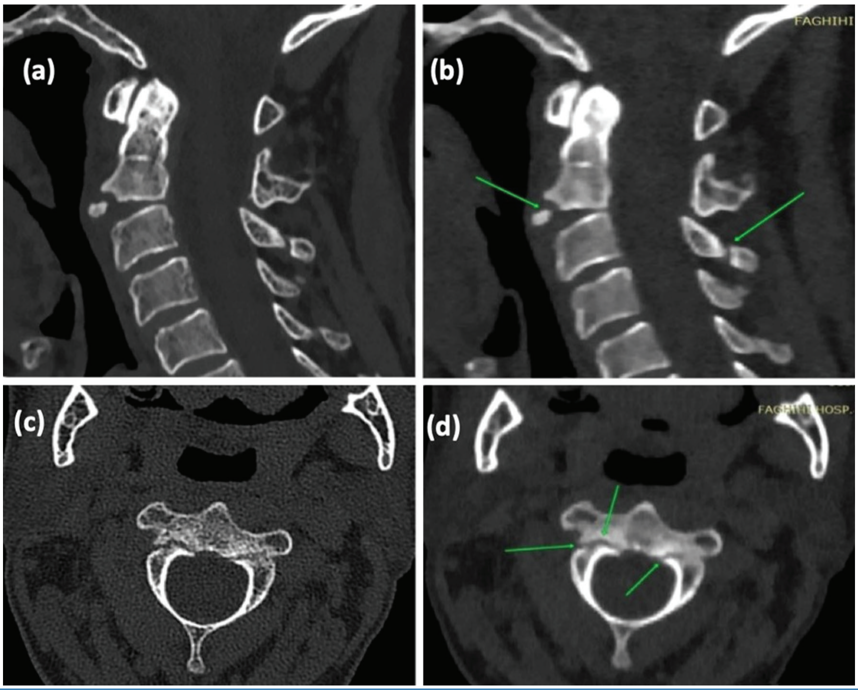

Figure 2: Multiple fractures of the cervical spine in a 50-year man (a) sagittal and (c) axial view taken by standard dose protocol with 1.13 mSv effective dose, and (b) sagittal and (d) axial view taken by Ultra-Low dose CT protocol with 0.03 mSv effective dose.

had bad quality, they reported six cases (9.8%) of ULD-CT images as bad quality. In other words, 90.1% of cases in ULD CT were of acceptable quality for the radiologist.

The frequency distribution of the standard dose and ULD-CT image quality assessment based on the scanned region, extremities (limbs), and spine are shown in figure 1. It can be seen from figures 1a and b that the total number of bone CT cases is 35 and 30 in the extremities (limbs) and spine regions, respectively.

The number of bone CT images of the extremities reported as very good and good quality is 35 out of 35 cases recorded by standard-dose CT protocol (figure 1a). In the cases of the extremity (limb) bone images acquired by the

ULD-CT protocol, 33 cases have acceptable diagnostic image quality, and two cases have bad image quality (figure 1b). The image quality of 30 (out of 30) cases was reported as very good and good for standard-dose CT protocol in the spine region (figure 1c). The number of cases with very good (1 case, 3%), good (15 cases, 50%), and medium (9 cases, 30.3%) image quality is 25 for spine bone CT recorded by the ultra-low dose protocol (figure 1d). The number of cases with undiagnosable image quality (bad image quality) was 5 (17%) for the spine-bone CT images taken by the ultra-low dose protocol (figure 1d).

Bone CT images are shown as samples in figure 2 (cervical spine) and figure 3 (humorous) to compare the diagnostic image quality of standard and ULD-CT protocols.

The results of the pathologic evaluation, done by radiologists, demonstrated that there was no pathological finding in 10 cases out of 65. The radiologists' report shows that 112 pathologies were found in standard-dose bone CT images. It has to be mentioned that the standard dose protocol is known as a gold standard. The number of detected pathologies in bone CT images acquired by the ULD protocol was 107 (about 96%). The overall sensitivity and specificity of ULD-CT images to diagnose pathologies compared to standard dose images were 67%-95% and 100%, respectively.

The pathology (bone trauma and disorders) findings for the standard dose and ULD-CT images are shown in figure 4.

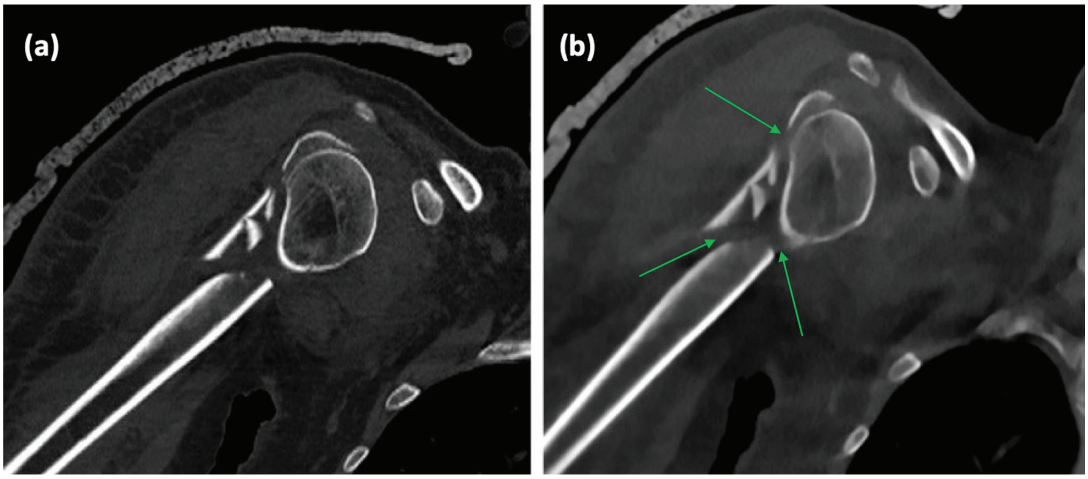

Figure 3: A sagittal view of comminute humorous bone fracture in a 61-year woman was taken by (a) standard dose CT protocol with 10.13 mSv, and (b) Ultra-Low dose CT protocol with 0.11 mSv effective dose.

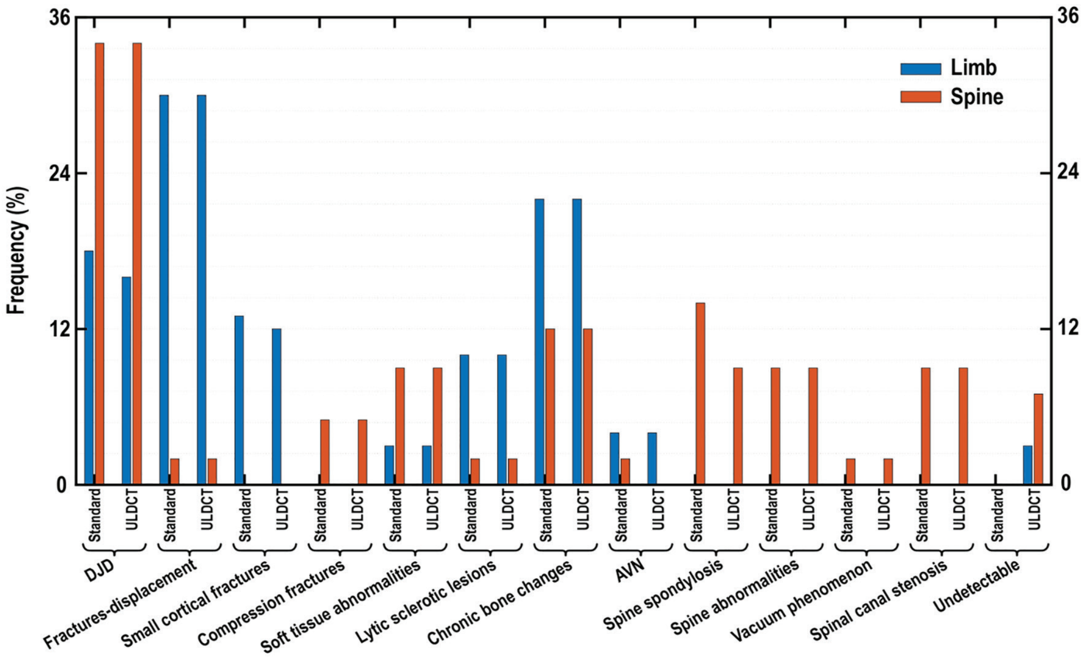

Figure 4: The percentage frequency of extremities (limbs) and spine pathologies that were detected by standard-dose and ultra-low-dose Computed Tomography (ULDCT) images. DJD and AVN are the abbreviations for "degenerative joint disease" and "avascular necrosis", respectively.

Figure 4 compares the bone trauma and disorders, of spine and limb (extremity) cases, detected by standard dose and ULD-CT images. As can be seen in figure 4, the percentage frequency of undetectable bone trauma and disorders in both spine and limb (extremity) cases taken by standard-dose CT protocol was 0.0%. It means that 100% bone trauma and disorders could be detected in both spine and limb cases by standard dose CT. The frequency percentage of bone trauma and disorders that could not be detected in CT images taken by ULD-CT protocol were 7% and 3% in spine and limb cases, respectively.

Discussion

The result of the present study showed that the ultra-low-dose CT images of extremities, limbs, and spines have adequate diagnostic image quality. It was shown that out of 112 pathologies detected by standard-dose CT protocol, 107 of them, i.e., about 96%, were recognized in ULD-CT images with about 95% (87%–99%) dose reduction. As explained in the section of the introduction, reducing kVp in the ULD-CT protocol reduces the number of x-ray photons and, as a result, the patient dose. Reducing patient dose, as mentioned earlier, increases image noise, which can distort image contrast and decrease image quality. On the other hand, decreasing kVp (photon energy) increases the photoelectric effect in materials with high effective atomic numbers, such as bone. Therefore, by decreasing kVp, the contrast between the extremity (limb), the spine bone, and the surrounding soft tissues increases considerably.[34]

Patient dose reduction in the ULD-CT protocol, due to the use of low mAs and low kVp compared to the standard dose CT protocol, increases image noise. Image noise interferes with image contrast; as a result, decreases image quality. The main reason for the acceptable quality of ULD-CT images, noise reduction, is due to the use of Iterative Model Reconstruction (IMR) level 2, in the present study. Iterative reconstruction, by reducing image noise, adequately improved image quality, as seen in this study.[35]

As it was expected, the dose reduction of thinner organs, such as the wrist, for the ULD-CT protocol was 87% compared to the standard dose. This is because the difference between ULD-CT kVp (used 80 kVp) and the standard dose (used 100 kVp) for the wrist was 20 kVp. The discrimination of kVp for the two protocols, standard dose, and ULD, was 40 kVp (120 kVp for standard dose and 80 kVp for ULD-CT) for the rest of the organs.

A study done by Xiao and colleagues showed that the ULD-CT can diagnose non-displaced fractures of extremities such as the shoulder, knee, ankle, and wrist.[36] Moreover, Konda and colleagues researched to evaluate the ULD-CT images with a 14 times dose reduction compared to standard-dose CT on limb fractures. The result of their study showed that the quality of ULD-CT images of the limb is acceptable and comparable to that of standard-dose CT.[14] The result of the present study demonstrated that the ULD-CT protocol, with a significant dose reduction compared to the standard dose, can diagnose extremity fractures and abnormalities.

Alagic and colleagues demonstrated that they could reduce the effective dose of wrist and ankle fractures by using the ULD-CT protocol. Their results showed that the patient dose in ULD-CT of the wrist and ankle was comparable to that of plain digital radiography of these regions. They stated that the ULD-CT images of extremities contain more detailed information about bone fractures than digital radiography. Therefore, they suggested that digital X-ray radiography of extremities could be replaced by ULD-CT.[7] The results of the present study showed that the ULD-CT protocol can decrease patient doses for the wrist (87%) and ankle (97%) with acceptable image quality. The mean effective dose of the patient for the ULD-CT of the extremity bone (including foot, wrist, and ankle) protocol is 0.004 mSv (0.001 mSv-0.006 mSv) in the present study, while the effective dose of the plain radiography of extremities is about 0.001 mSv, as was reported in the study of Alagic and colleagues.[7]

The results of a study done by Koivisto and colleagues showed that the effective dose of the elbow region due to the standard dose CT and conventional radiography were about 0.04 mSv and 0.0015 mSv. The effective dose for the patient, in the elbow region imaging, is about 0.07 mSv and 0.005 mSv for conventional and ULD-CT (0.005 mSv) protocols in the present study. The differences between the results of our study and Koivisto and colleagues can be attributed to the differences between the types of the two CT systems.[37]

Jeon and colleagues conducted a study to measure the effective dose of the digital radiography of (a) full-length spine and (b) full-length lower extremity. Their results demonstrated that the effective doses of the full spine and full extremity taken by standard dose radiography were 11.52 mSv and 10.19 mSv, respectively.[38] They used many plain X-rays to get full-length images of the spine and lower extremities by stitching images together. In the present study, the estimated effective dose of the ULD-CT for the whole spine, cervical+thoracic+lumbosacral, and lower extremity, hip+leg+knee+ankle, were 0.4 mSv and 0.13 mSv, which are less than those values for full-length spine and lower extremities reported by Jeon and colleagues.

As a sample, the Diagnostic Reference levels (DRL) of the conventional radiography reported, based on effective dose in mSv (milli-Sivert), for cervical (anterior view+lateral view), thoracic (anterior view+lateral view), and lumbosacral (anterior view+lateral view) spines are 0.053 mSv, 0.3462 mSv, and 0.56 mSv, respectively.[39] The effective doses of the cervical spine, thoracic spine, and lumbosacral spine scanned by ULD-CT protocol estimated in the present study are 0.04 mSv, 0.14 mSv, and 0.17 mSv, respectively. It is clear that the effective dose of the ULD-CT protocol of the cervical spine, thoracic spine, and lumbosacral spine, which are presented in the this study, is comparable to that of the conventional radiography. Therefore, the ULD-CT images of the spine and extremities can substitute the plain conventional X-ray images of these structures, while the previous can detect more normal and abnormal details of bones.

In a similar study, Tuncer and colleagues conducted research on 98 patients suspected of ankle fractures. They evaluated the ULD-CT images, which were taken immediately after conventional scanning. Their results showed that the image quality of the ULD-CT was acceptable and valid to detect ankle fractures in patients suspected of ankle fractures. Their results are in line with the present study. They concluded that the effective dose of the patients suspected of ankle fracture due to the ULD-CT is less than that of multiple views of the plain X-ray.[31]

It has to be noted that the mean of the total effective dose to the patient received from standard and ULD-CT protocols in the present paper is very close to the Diagnostic Reference Level of the spine (cervical, thoracic, and lumbosacral spine) presented in standard texts. As an example, the result of the mean of the total effective dose, ULD-CT plus standard dose CT of the spine, in the present study and DRLs are 5.16 mSv and 5.0 mSv, respectively. We can conclude that the effective dose for the patients who signed the consent form and took part in the present study is comparable to those DRLs reported by the regulatory health services.[39]

In a study done by Mulkens and others, the patient dose was evaluated for low-dose and standard-dose CT protocols for the cervical spine. They did not change the kVp, with 120 kVp being fixed in both standard and low-dose CT protocols, but reduced mAs from 175 in the standard dose to 68 in the low-dose protocol. The estimated effective dose to the patient for standard dose CT images of the cervical spine were close to each other in Mulkens and colleagues (3.75 mSv) and the present study (2.08 mSv). While the estimated effective dose reduction in Mulken's study was about 53% and it was about 98% in this study, the diagnostic image quality was still acceptable for the cervical spine in the present case.[40]

The limitation of the present study was that we evaluated the image quality subjectively based on the radiologist's reports.

Conclusion

Ultra-low-dose CT images of extremity (limb) and spine bones, reconstructed by the iterative reconstruction algorithm (IMR level 2), possess sufficient diagnostic quality to detect bone fractures and bone disorders or abnormalities.

Acknowledgment

The authors thank Shiraz University of Medical Sciences for their encouragement and financial support (code:19766).

Authors' Contribution

R. R: Designed the study, writing and revising the paper; F. Z: Designed the study, revising the paper; S.M. A, S. D.Z: Collecting data, conducting the experimental study, revising the paper; A. J, V. A, S. Ch, S. A. M: Interpretation of data and assisted with the implementation of the study and writing and revising the paper. All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflict of Interest: None declared.

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