Original Article | Musculoskeletal Imaging

eISSN 2005-8330
https://doi.org/10.3348/kjr.2020.0640
Korean J Radiol 2021;22(5):782-791

Korean Journal of Radiology
KJR

Depiction of the Periosteum Using Ultrashort Echo Time Pulse Sequence with Three-Dimensional Cone Trajectory and Histologic Correlation in a Porcine Model

Dae Joong Kim[1], Kun Hwang[2], Hun Kim[2], Jang Gyu Cha[3], Hyungseok Jang[4], Ju-Yong Park[5], Yeo Ju Kim[5]

Departments of [1]Anatomy, [2]Plastic Surgery, and [5]Radiology, College of Medicine, Inha University, Incheon, Korea; [3]Department of Radiology, Soonchunhyang University Hospital, Bucheon, Korea; [4]Department of Radiology, University of California, San Diego, La Jolla, CA, USA

Objective: To evaluate the signal intensity of the periosteum using ultrashort echo time pulse sequence with three-dimensional cone trajectory (3D UTE) with or without fat suppression (FS) to distinguish from artifacts in porcine tibias.
Materials and Methods: The periosteum and overlying soft tissue of three porcine lower legs were partially peeled away from the tibial cortex. Another porcine tibia was prepared as three segments: with an intact periosteum outer and inner layer, with an intact periosteum inner layer, and without periosteum. Axial T1 weighted sequence (T1 WI) and 3D UTE (FS) were performed. Another porcine tibia without periosteum was prepared and subjected to 3D UTE (FS) and T1 WI twice, with positional changes. Two radiologists analyzed images to reach a consensus.
Results: The three periosteal tissues that were partially peeled away from the cortex showed a high signal in 3D UTE (FS) and low signal on T1 WI. 3D UTE (FS) showed a high signal around the cortical surface with an intact outer and inner periosteum, and subtle high signals, mainly around the upper cortical surfaces with the inner layer of the periosteum and without periosteum. T1 WI showed no signal around the cortical surfaces, regardless of the periosteum state. The porcine tibia without periosteum showed changes in the high signal area around the cortical surface as the position changed in 3D UTE (FS). No signal was detected around the cortical surface in T1 WI, regardless of the position change.
Conclusion: The periosteum showed a high signal in 3D UTE and 3D UTE FS that overlapped with artifacts around the cortical bone.
Keywords: *UTE; Periosteum; 3D cone trajectory*

INTRODUCTION

Almost every bone in the body is covered by the periosteum [1]. The periosteum is a complex structure comprising an outer fibrous layer that lends structural integrity and an inner cambium layer with osteogenic potential [1]. During growth and development, the periosteum contributes to bone elongation and modeling and participates in bone recovery from injury [1]. The periosteum is the main target of many diseases, including hypertrophic osteoarthropathy, stress reaction, and autoimmune and inflammatory diseases [1]. Despite its importance, the periosteum has received little attention as it is not visible on conventional MRI [1,2]. Conventional MRI has shown that T2 relaxation is sensitive to the distribution of water content in musculoskeletal tissues [2]. The periosteum comprises primarily tissues with tightly bound protons, resulting in very short T2 relaxation times of 5.3 to 11.4 msec [2]. Thus, little or no signal is detectable by conventional MRI sequences employing a relatively long echo time (TE) [2,3]. Ultrashort TE pulse sequence (UTE) is an emerging MR technique that uses dramatically shortened TE, typically in the order of microseconds [2,3], which allows for the visualization of short T2 components

Received: May 25, 2020 **Revised:** August 16, 2020
Accepted: October 14, 2020
This work was supported by an Inha University Research Grant.
Corresponding author: Yeo Ju Kim, MD, PhD, Department of Radiology, College of Medicine, Inha University, 27 Inhang-ro, Jung-gu, Incheon 22332, Korea.
• E-mail: kimyeojurad@gmail.com

Korean Journal of Radiology
KJR

with high signal intensity [3]. UTE imaging with high spatial resolution has been successfully applied to visualize tissue with primarily short T2 components in spinal disks, osteochondral junctions, and cortical bone [4,5]. In terms of the periosteum, a few studies using two-dimensional (2D) or three-dimensional (3D) UTE reported that a high signal region, corresponding to the periosteum, was visualized adjacent to the cortical surface of the ovine tibia, porcine fibula, and at several sites in healthy human volunteers and patients with osteoarthritis [2,6]. However, the signal that was attributed to the periosteum in prior studies needs to be differentiated from artifacts in tissue boundary, as well as partial volume effects, considering that the periosteum is a very thin structure and is located over the curved surfaces of bones [2,6-8].

Of the various UTE techniques, 2D UTE is particularly sensitive to partial volume artifacts, eddy currents, field homogeneity, and gradient non-linearity [9]. Half-pulse excitation of the 2D UTE requires the summation of two acquisitions with the slice selection gradient polarity reversed so that a conventional slice profile can be formed [9-11]. Gradient profile distortion may result in improper weighting of the excitation and mismatch between the two acquisitions with non-ideal cancellation [9-11]. Compared with 2D UTE, high-resolution 3D isotropic UTE imaging, such as UTE with 3D cone trajectory, has a distinct advantage because it can detect short T2/T2*signals, as well as reduce the impact of susceptibility differences and partial volume effects [9,10,12]. In addition, UTE with a 3D cone trajectory provides volumetric coverage and a reduced scan time, increased readout efficiency, and sampling density uniformity [12,13].

The purpose of our study was to evaluate the signal intensity of the periosteum using UTE with 3D cone trajectory (3D UTE) with or without fat suppression (FS) to distinguish signals from artifacts in porcine tibiae.

MATERIALS AND METHODS

This study involved three different experiments, all of which were exempt from Institutional Review Board approval and for which informed consent was not required. The first experiment evaluated whether 3D UTE (FS) could depict the periosteum more accurately than T1 weighted sequence (T1 WI). Furthermore, we correlated these findings with histological examination. The second experiment evaluated the signals around cortical surfaces with or without the periosteum, and the third experiment evaluated artifacts around the cortical surfaces without the periosteum.

Experiment 1: Depiction of the Periosteum in 3D UTE (FS) and T1 WI with Histologic Correlation

Preparation of Periosteal Tissue

Three porcine lower legs obtained within 24 hours of death were prepared. A plastic surgeon partially peeled off the periosteum and overlying skin from the medial cortex of the tibia in a rectangular shape for all three tissues. One side of the peeled periosteum was left to allow connectivity with the adjacent normal tissue. A generous amount of ultrasound transmission gel (Aquasonic clear gel, Parker Laboratories Inc.) was placed in the gap between the partially detached periosteum and the medial cortex of the tibia.

MRI Protocol

MRI was performed using 3T MR scanners (MR750W, GE Healthcare) with a maximum gradient amplitude of 44 mT/m and a maximum slew rate of 200 mT/m/ms. The imaging protocol consisted of axial T1 WI, 3D UTE, and 3D UTE FS (Table 1). The 3D UTE sequence utilized a short nonselective hard pulse (duration = 100 μs) for volumetric excitation, followed by dual-echo 3D cone acquisition (Supplementary Fig. 1) [12-14]. The first free induction decay acquisition with a TE of 32 μs detected signals from both long- and short-T2 components, whereas the second echo with a TE of 6.6 ms detected signals from longer-T2 components. Subtraction of the second echo from the first suppresses signals from the longer-T2 components and typically provides high contrast for tissues whose T2* lies between the two TEs. We utilized this dual-echo acquisition with echo subtraction to suppress long T2 signals [14]. The scan times were 3 minutes 30 seconds for T1 WI, 4 minutes 14 seconds for 3D UTE, and 9 minutes 26 seconds for 3D UTE FS (Table 1).

Image Analysis and Correlations with Histological Findings

After the MRI scan, the stripped periosteal tissues were completely detached, fixed using 4% neutral buffered formalin and embedded in paraffin blocks. After this routine histological process, cut into 10-μm-thick sections, stained with Masson's trichrome stain, and observed under light microscopy by a histologist. Two musculoskeletal

 https://doi.org/10.3348/kjr.2020.0640

Table 1. MRI Protocol

	3D UTE		3D UTE FS		T1 WI
	1st Echo	2nd Echo	1st Echo	2nd Echo	
TR (msec)	15.1		15.1		793
TE (msec)	0.032	6.6	0.032	6.6	7.66
FA (°)	17		17		111
BW (kHz)	62.5		62.5		62.5
Matrix size	NA		NA		300 x 300
Readout matrix	324		324		
Number of projections	20217		20217		
ST/gap (mm)	3/0		3/0		3/0
FOV (mm)	150		150		150
Scan time	4:14		9:26		3:40

BW = bandwidth, FA = flip angle, FOV = field of view, FS = fat suppression, ST = section thickness, TE = echo time, TR = repetition time, T1 WI = T1 weighted sequence, 3D UTE = ultrashort echo time pulse sequence with three-dimensional cone trajectory

radiologists (with 10 or 20 years of experience) evaluated the signal intensity of the partially detached periosteal tissues and the medial tibial cortical surface from which the periosteum had been peeled for histologic correlation. The signal intensity was graded as a relatively clear signal (+++), mild signal with blurring (++), weak signal with blurring (+), partial presence of a weak signal with blurring (+/-), and low or no signal indistinguishable from the cortex (-).

Experiment 2: Evaluation of Signals Around Cortical Surfaces with or without the Periosteum

A tibia was extracted from another porcine lower leg, and the soft tissue was removed, leaving the periosteum intact. The tibia was divided into three segments and prepared as follows: the periosteum was left in the proximal 1/3 segment; the periosteum was peeled away from the tibia in the middle 1/3 segment; or the periosteum was peeled away from the tibia, and the outer cortex was scraped in the distal 1/3 segment.

After preparation, the samples were placed in a small container filled with gelatin gel, and MRI was performed using the same sequence as in experiment 1. The same radiologists who evaluated the images of the 1st experiment analyzed the images of prepared tissue with a consensus, but without awareness of the tissue preparation. They assessed the signal intensity around the outer surface of the tibia and graded it in the same manner as in the 1st experiment.

After the MRI scan, the three tibial segments were fixed using 10% buffered formalin, decalcified in Cal Ex II (Fisher Scientific) for 48 hours, and prepared for histologic analysis, as described in experiment 1. The histological sections were subjected to hematoxylin and eosin staining. The stained slides were digitally imaged at 340 magnification (model SCN400; Leica Microsystems) and examined to determine if the tissue preparation was successful.

Experiment 3: Artifacts Around Cortical Surfaces without the Periosteum

Another tibia was extracted from a different porcine lower leg with complete removal of the periosteum and scraping of the outer cortex. This was then placed in a small container filled with gelatin gel.

MRI was performed twice with T1 WI, 3D UTE, and 3D UTE FS with the container placed right-side-up and upside-down. The T1 WI, 3D UTE, and 3D UTE FS parameters were the same as those used in the 1st and 2nd experiments.

The same radiologists who evaluated the images of the 1st and 2nd experiments analyzed the MR images with a consensus, but without awareness of the tissue preparation. They assessed the presence and location of signal intensity around the cortical surface depending on positional changes using the same grading system as the first experiment.

RESULTS

Experiment 1: Depiction of the Periosteum in 3D UTE (FS) and T1 WI with Histologic Correlation

The periosteum was observed on the undersurface of the peeled tissues during histological examination (Fig. 1, Table 2). MRI showed the periosteum as a very thin low signal on T1 WI, but a relatively clear high signal in the 1st echo, and a blurred high signal in the subtraction images of 3D UTE and 3D UTE FS in all three tissues (Fig. 1). However, the

https://doi.org/10.3348/kjr.2020.0640

Korean Journal of Radiology
KJR

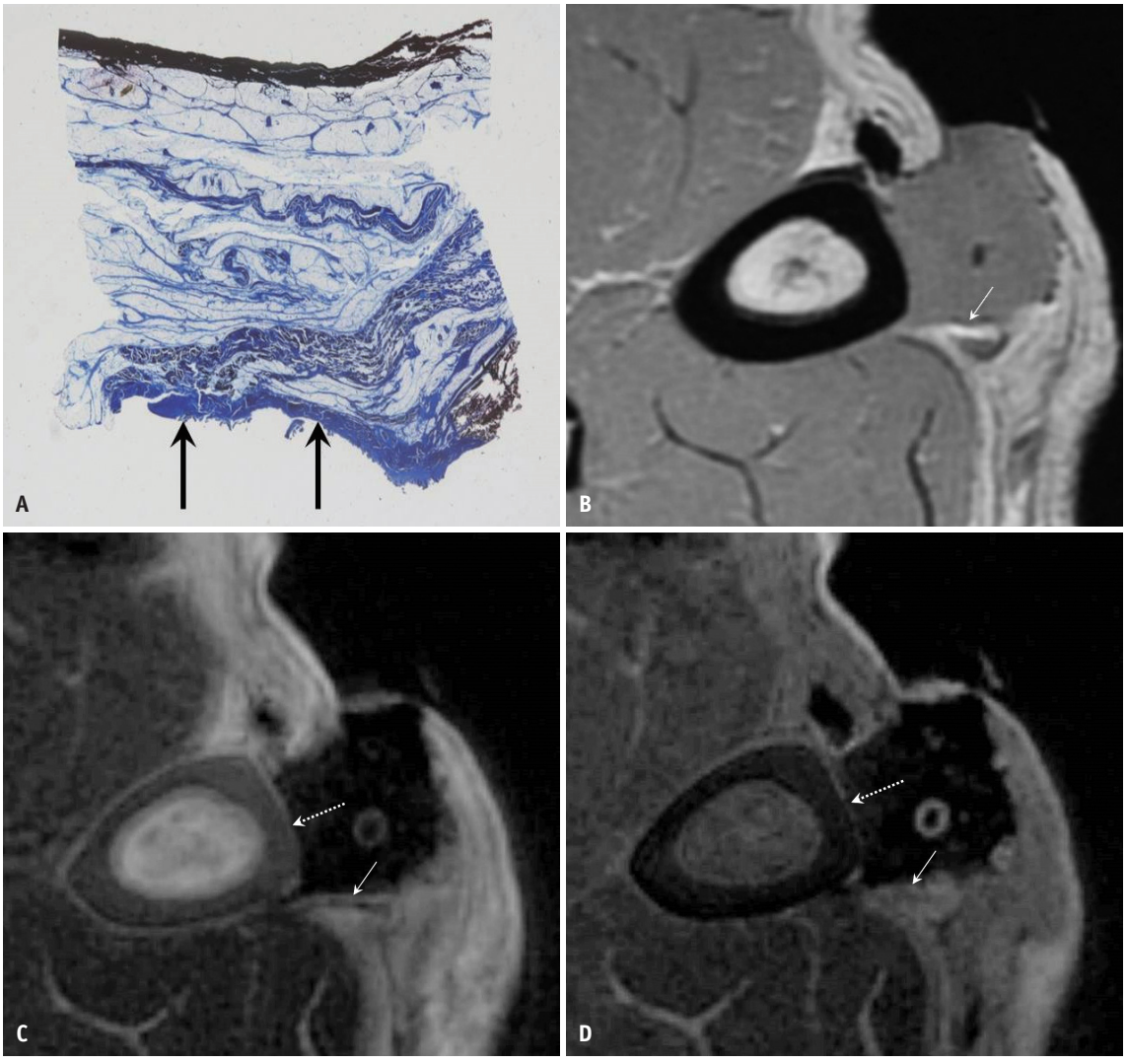

Fig. 1. Photomicrograph (A, Masson's trichrome, x 10) and MRI findings (B-D) of a porcine tibia stripped of periosteal tissue. The periosteum (arrows) was confirmed histologically at the peeled off tissue **(A)**. Axial T1 weighted sequence **(B)** showing a very thin signal of low intensity (arrow) on the undersurface of the peeled tissue, and no signal at the cortical surface. The subtraction image **(C)** of 3D UTE shows a thick high signal at the undersurface of peeled off tissue (arrow) and at the cortical surface (dashed arrow). The subtraction **(D)** image of 3D UTE with fat suppression shows less apparent high signal intensity on the undersurface of peeled off tissue (arrow) and the cortical surface (dashed arrow) than 3D UTE. 3D UTE = ultrashort echo time pulse sequence with three-dimensional cone trajectory

periosteum was less apparent in the 3D UTE FS compared to the 3D UTE in all tissues. The medial tibial cortical surface, from which the periosteum had been peeled, showed no discernible signal on T1 WI, but showed high signal intensity in the 3D UTE and 3D UTE FS (Fig. 1, Table 2).

Experiment 2: Evaluation of Signals Around Cortical Surfaces with or without the Periosteum

The histological slides of the proximal 1/3 portion of the tibia, on which the periosteum remained, showed intact inner fibrous and outer osteogenic layers of the periosteum (Fig. 2A). 3D UTE and 3D UTE FS showed a high signal around the cortical surface with low signal intensity of edge thickening at the bottom side of the cortex. The 2nd echo image showed a less apparent high signal around the cortical surface and more prominent low signal intensity of edge thickening at the bottom side of the cortex than those of the 1st echo image (Fig. 2, Supplementary Fig. 2, Table 2). The periosteum signal was much less apparent in the 3D UTE FS than the 3D UTE (Table 2).

The histological slides of the 1/3 portion of the tibia in which the periosteum had been peeled away, demonstrated a thin inner layer of the periosteum at the outer surface of the tibia (Fig. 3A). The 3D UTE and 3D UTE FS showed

https://doi.org/10.3348/kjr.2020.0640

Table 2. Results of the Imaging Analysis of the 1st, 2nd and the 3rd Experiment

Tissue	3D UTE			3D UTE FS			T1 WI
	1st Echo	2nd Echo	Sub	1st Echo	2nd Echo	Sub	
1st experiment							
Stripped periosteum	+++	+	++	++	+	+	-
Cortical surface	++	+	++	+	+	+	-
2nd experiment							
Cortex with superficial and deep layer of periosteum							
Top	+++	+	+++	++	+	++	-
Bottom	++ LE (+)	- LE (++)	++ LE (++)	+/- LE (+)	- LE (++)	+ LE (++)	-
Cortex with deep layer of periosteum							
Top	+	+	+	+	+	+	-
Bottom	+/- LE (+)	- LE (++)	+ LE (++)	- LE (+)	- LE (++)	+ LE (++)	
Cortex without periosteum							
Top	+	+	+	+	+	+	-
Bottom	+/- LE (+)	- LE (++)	+ LE (++)	- LE (+)	- LE (++)	+ LE (++)	-
3rd experiment							
Cortex without periosteum (right sided up position)							
Top	+	+	++	+	+	++	-
Bottom	+/- LE (+)	- LE (++)	+ LE (++)	- LE (+)	- LE (++)	+ LE (++)	- LE (++)
Cortex without periosteum (upside down position)							
Top	+/- LE (+)	- LE (++)	+ LE (++)	- LE (+)	- LE (++)	+ LE (++)	- LE (++)
Bottom	+	+	++	+	+	++	-

FS = fat suppression, LE (+) = mild low signal intensity thickening at the cortical edge, LE (++) = intense low signal intensity thickening at the cortical edge, Sub = subtraction image of the second echo image from the first echo image, T1 WI = T1 weighted sequence, 1st = the 1st experiment (depiction of periosteum in 3D UTE [FS] and T1 WI with histologic correlation), 2nd = the 2nd experiment (evaluation of signals around cortical surfaces with or without the periosteum), 3rd = the 3rd experiment (artifacts around cortical surfaces without the periosteum), 3D UTE = ultrashort echo time pulse sequence with three-dimensional cone trajectory, + = weak high signal with blurring, ++ = mild high signal with blurring, +++ = relatively clear high signal, +/- = partly presence of subtle, weak signal with blurring

high signal intensity around the cortical surface, with low signal intensity of edge thickening at the bottom side of the cortex (Fig. 3, Supplementary Fig. 3, Table 2). The high signal was mainly observed around the top side of the cortical surface and was much weaker than the signal around the cortical surface with an intact periosteum. Again, the 2nd echo image showed a less apparent high signal around the cortical surface and more prominent low signal intensity of edge thickening at the bottom side of the cortex compared to those of the 1st echo image (Fig. 3, Supplementary Fig. 3, Table 2).

The histological slide of the distal 1/3 segment of the tibia in which the periosteum had been peeled away and the outer cortex had been scraped showed no periosteum at the outer cortex of the tibia (Fig. 4A). However, it showed almost the same imaging findings as the images of the mid 1/3 portion of the tibia, which has a thin inner layer of periosteum (Fig. 4, Supplementary Fig. 4, Table 2).

In contrast to 3D UTE and 3D UTE FS, T1 WI showed no discernible signal around the cortical surface in any of the three tibial segments (Supplementary Figs. 2-4, Table 2).

Experiment 3: Artifacts Around Cortical Surfaces without the Periosteum

In 3D UTE and 3D UTE FS, the tibial cortex with complete removal of periosteum showed a high signal around the cortical surface, but the location changed depending on the tissue position. In the right-side-up position there was a high signal around the top side of the cortical surface, and low signal intensity of edge thickening at the bottom side

https://doi.org/10.3348/kjr.2020.0640

Korean Journal of Radiology
KJR

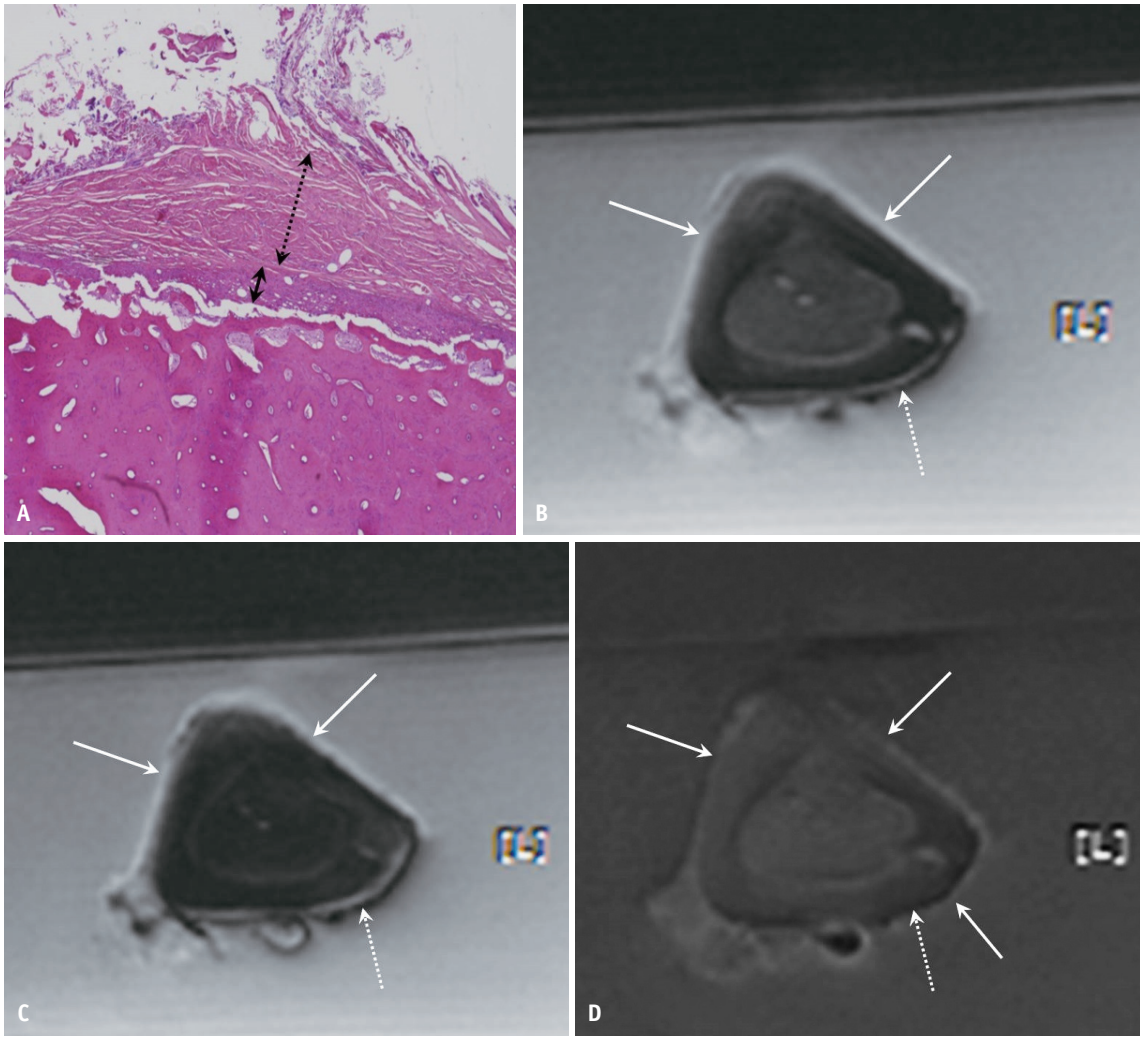

Fig. 2. Photomicrograph (hematoxylin & eosin stain, x 100) and images of 3D UTE FS of a porcine tibia with retained periosteum (A-D). Images of T1 weighted sequence and 3D UTE are shown in Supplementary Figure 2. The intact inner fibrous (short double-headed arrow) and outer osteogenic layer (long dashed double-headed arrow) of the periosteum in the photomicrograph **(A)**. The 1st **(B)** and 2nd **(C)** echo images of 3D UTE FS show high signal intensity (arrows) around the cortical surface, with a less apparent signal for the 2nd echo image **(C)** than that of the 1st echo image **(B)**. The bottom side of the cortex showed low signal intensity thickening at the cortical edge (dashed arrows), which is more prominent in the 2nd echo image than the 1st echo image. The subtraction image **(D)** shows high signal intensity (arrows) surrounding the whole cortex with a mildly thickened edge on the bottom side of the cortex (dashed arrow). FS = fat suppression, 3D UTE = ultrashort echo time pulse sequence with three-dimensional cone trajectory

of the cortex in the 1st and 2nd echo images of 3D UTE and 3D UTE FS (Fig. 5, Supplementary Fig. 5). However, in the upside-down position, the areas of high signal intensity and low signal intensity of edge thickening were switched (Fig. 5, Supplementary Fig. 5, Table 2). In the subtraction images, both 3D UTE and 3D UTE FS showed high signal intensity around all surfaces of the cortex.

T1 WI showed no discernible signal around the cortical surface, regardless of the position. However, low signal intensity of edge thickening was seen around the cortical surface, which was distant from the surface coil, such as the bottom side of the cortex in the right-side-up position and top side of the cortex in the upside-down position (Supplementary Fig. 4, Table 2).

DISCUSSION

In our study, 3D UTE and 3D UTE FS depicted the periosteum as high signals that were differentiated from the signal of the bony cortex, in contrast to the conventional T1 WI where no differentiation was seen. However, artifacts around the cortical surface, which mimicked or decreased the periosteal signals, were also observed.

Reichert et al. [2] reported that the normal periosteum,

 https://doi.org/10.3348/kjr.2020.0640

as well as alterations due to age, acute fracture, or chronic injury, can be readily visualized using 2D UTE imaging. In the study of Ma et al. [6], 3D UTE with double echo sequence also showed a high signal within the detached periosteum, corresponding to the findings of our study. The partially detached periosteum in the first experiment of our study showed high signal intensity in the 1st echo, 2nd echo, and subtraction images of 3D UTE and 3D UTE FS,

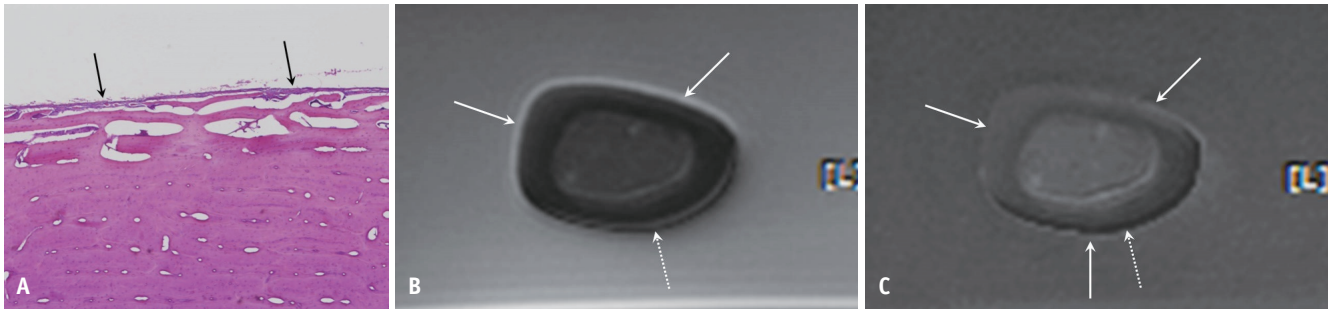

Fig. 3. Photomicrograph (A, hematoxylin & eosin stain, x 100) and images of 3D UTE FS (B, C) of a porcine tibia with periosteum peeled away. Images of T1 weighted sequence and the whole series of images of the 1st echo, 2nd echo, and subtraction images of 3D UTE and 3D UTE FS are shown in Supplementary Figure 3. The photomicrograph **(A)** shows the thin inner layer of the periosteum (arrows) along the outer cortex of the tibia. The 1st echo image **(B)** of the 3D UTE FS shows high signal intensity (arrows) around the cortical surface, mainly on the top side. The bottom side of the cortex shows low signal intensity thickening at the edge of the cortex (dashed arrow). The subtraction image **(C)** of the 3D UTE FS shows high signal intensity (arrows) surrounding the whole cortex with mild thickening of the edge of the bottom side of the cortex (dashed arrow). FS = fat suppression, 3D UTE = ultrashort echo time pulse sequence with three-dimensional cone trajectory

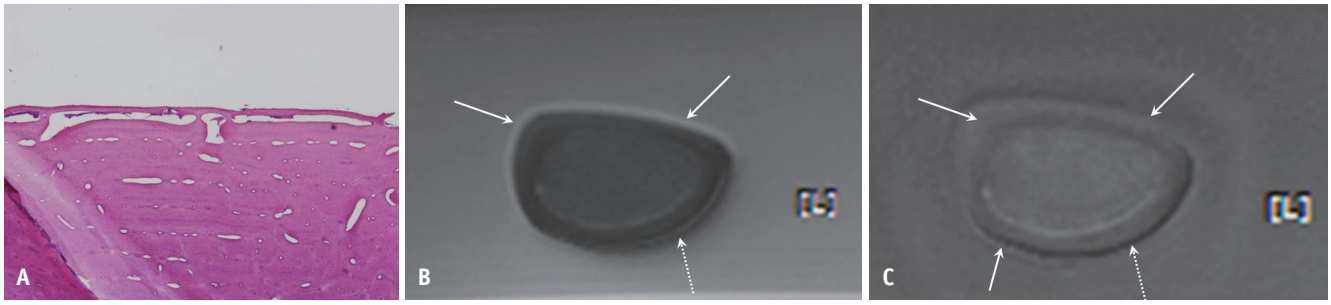

Fig. 4. Photomicrograph (A, hematoxylin & eosin stain, x 100) and images of 3D UTE FS (B, C) of a porcine tibia with removed periosteum and scraping of the outer cortex. Images of T1 weighted sequence and the whole series of images of the 1st echo, 2nd echo, and subtraction images of 3D UTE and 3D UTE FS are shown in Supplementary Figure 4. The photomicrograph **(A)** shows no periosteum at the outer cortex of the tibia. The 1st echo image **(B)** of the 3D UTE FS shows high signal intensity (arrows) around the cortical surface, mainly on the top side. The bottom side of the cortex shows low signal intensity thickening at the edge of the cortex (dashed arrow). The subtraction image **(C)** of the 3D UTE FS shows high signal intensity (arrows) surrounding the whole cortex, with a mild thickening at the edge of the bottom side of the cortex (dashed arrow). FS = fat suppression, 3D UTE = ultrashort echo time pulse sequence with three-dimensional cone trajectory

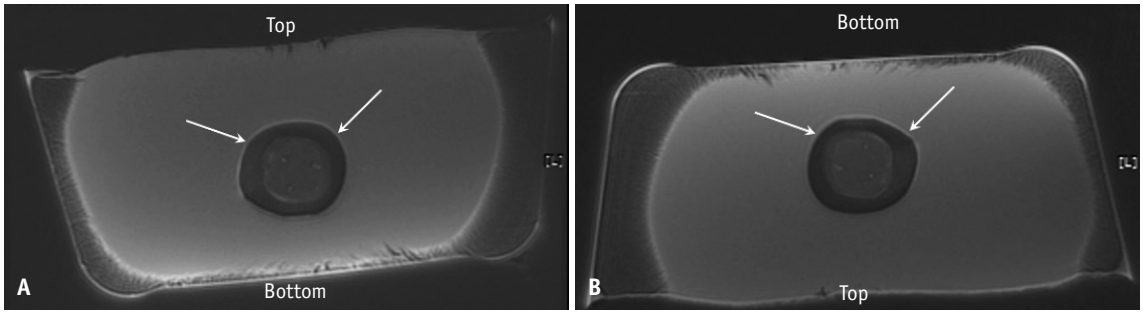

Fig. 5. The 1st echo images of 3D UTE FS of a porcine tibia with removed periosteum and scraping of the tibial cortex placed into a container filled with gelatin gel.
Images were obtained with the container placed right-side-up **(A)** and upside-down **(B)**. The whole series of images of the 1st echo, 2nd echo, and subtraction images of 3D UTE and 3D UTE FS and T1 weighted sequence are shown in Supplementary Figure 5. **A.** The 1st echo image of UTE FS with the container right-side-up shows high signal intensity (arrows) around the upper portion of the cortex. **B.** Same sequence with the container upside-down shows a changing area of high signal intensity (arrows) on the bottom side. FS = fat suppression, 3D UTE = ultrashort echo time pulse sequence with three-dimensional cone trajectory

https://doi.org/10.3348/kjr.2020.0640

Korean Journal of Radiology
KJR

which were confirmed by histology. However, a high signal intensity was also observed along the cortical surface from which the periosteum had been peeled in our study, similar to the observation reported in ovine tibia after periosteum removal in the study by Reichert et al. [2]. They assumed that the high signal intensity along the cortical surface might be due to a residual inner layer of the periosteum or an artifact [2]. Thus, our 2nd experiment focused on the evaluation of signals around cortical surfaces with or without the periosteum.

In the 2nd experiment, the tibia with intact periosteum showed relatively clear or mild high signal intensity in the images of 3D UTE and 3D UTE FS; this was confirmed by histology and supported the results of the 1st experiment. However, tibias with a thin inner layer of the periosteum and with complete removal of the periosteum also showed a thin high signal intensity along the cortical surface, although the signal intensity was less apparent and mainly visible around the top side of the cortical surface. The subtraction images of the tibia with and without the periosteum showed high signal intensity around the cortical surface. This suggested that the remaining high signal intensity around the cortical surface from which the periosteum was stripped in the 1st experiment was likely an artifact, rather than a residual inner layer of the periosteum.

In the 3rd experiment for evaluation of the artifacts around cortical surfaces without the periosteum, the bone after removal of the periosteum in the right-side-up position showed accentuated high signal intensity on the top side of the cortical surface, and the bottom side showed low signal intensity of thickening of the cortical edge. In the upside-down position of the same tissue, a high signal intensity area occurred on the bottom side of the container, whereas the top portion showed a low signal. The change in the high signal intensity area, depending on the position, suggested that the signal was an artifact and not from a true anatomical structure. A variety of artifacts occur with UTE, including eddy currents, gradient timing errors, directional susceptibility, and chemical shift [2,7,8]. Although 3D UTE is less sensitive to eddy currents and gradient timing errors than 2D UTE, these could lead to strong artifacts at the tissue boundary [2,7,8,15,16]. In the MR system, gradient waveforms are often far from ideal, due to current induction from the rapidly changing gradients, the so-called eddy currents [7]. Eddy currents may delay and distort the gradient waveform. The modern clinical MR system addresses this issue by correcting for the delay (i.e., timing error) and by applying pre-emphasis to the input gradient; however, it is designed for conventional Cartesian imaging utilizing only the gradient plateau for data readout, which does not correct for errors in the entire gradient waveform [7,11,16]. Therefore, UTE techniques based on ramp-sampling tend to suffer from residual imperfections in the gradient [7,16], which may decrease the image quality and make image analysis challenging if not compensated in the image reconstruction (i.e., k-space trajectory calibration), especially for inexperienced observers [17,18]. While the dual-echo acquisition with echo subtraction increases image contrast, it also lowers the signal-to-noise ratio [14]. Small differences in the regridding reconstruction timing between the first and later echoes used in the subtraction images could also generate similar artifacts [2]. Directional susceptibility effects could also be a source of high signals around the tissue boundary in the subtraction images of 3D UTE and 3D UTE FS [2]. In our study, low signal intensity thickening of the cortical edge was observed at the bottom side of the tibial cortex in T1 WI and 3D UTE (FS). In 3D UTE (FS), it was more prominent in the 2nd echo images, compared to the 1st echo image, reflecting susceptibility artifacts (i.e., signal drop-out), which worsened with a longer TE in GRE imaging due to local field inhomogeneity. The directional susceptibility artifact of the 2nd echo image in 3D UTE (FS) not only reduced the periosteum signal when it was intact, but may also produce artifactual high signal differences around the cortical surface in the echo subtracted images [2,19,20]. Lastly, a chemical shift may appear in the frequency direction with an adjacent absence of signal in the conventional Cartesian sequence which may take the form of boundary displacement with radial or cone trajectory sequences, such as the 3D UTE used in the present study. This increases with field strength and the use of lower-receiver bandwidths but should disappear with FS [21]. In our study, the high signal intensity along the surface of the cortex without any periosteum did not disappear with FS; therefore, it might not have occurred because of a chemical shift.

Artifacts falsely simulating the periosteum can also reduce the periosteum signal [2]. Eddy currents may have also played a role in reducing the signal from the first echo relative to later echoes [2]. The susceptibility artifacts extending from the bone at later TEs could also reduce the periosteal signal. Overall, the visualization of the periosteum was limited by the system's signal-to-noise

 https://doi.org/10.3348/kjr.2020.0640

ratio. Subtraction images often made the periosteum more conspicuous, but these were limited by the signal-to-noise ratio, including the additional noise introduced by the subtraction process.

Our study proved that the periosteum showed a high signal in 3D UTE, which was slightly less apparent in 3D UTE FS. Although FS generally made the periosteum more conspicuous, it could also partially saturate and reduce its overall signal intensity. To suppress the long T2 signal, we used dual-echo acquisition with echo subtraction [14]. This technique is simple, time-efficient, and provides high contrast between short and long T2 signals, despite some loss in the signal-to-noise ratio [14].

Our study has several limitations. The small number of tissue samples analyzed did not allow for statistical analysis to be performed. Second, images were not analyzed independently, but with a consensus. However, because UTE has not been used clinically, even experienced musculoskeletal radiologists are not familiar with UTE imaging; thus, consensus analysis was likely more accurate than independent analysis. Third, the UTE signal of the periosteum and the artifact of the tissue boundary can be affected by the coil, surrounding tissue, and tissue preparation. Fourth, our study did not include clinical cases with periosteal pathology, so the diagnostic value of the 3D UTE cone is still unclear. However, given that accurate validation of the periosteum signal differentiation from artifacts should precede clinical studies, our study will provide the basis for further clinical research.

Our study shows the ability of the depiction of periosteum in 3D UTE as well as its limitations. For clinical translation, our study highlights artifact reduction in tissue boundaries and may be essential for imaging of the periosteum in 3D UTE, as well as increased spatial resolution. Follow-up studies for conditions with the periosteal reaction, such as fracture healing, osteomyelitis, tumor, and spondyloarthropathies are needed to understand the clinical implications of 3D UTE [22].

In conclusion, the periosteum showed high signals in 3D UTE and 3D UTE FS, but overlapped with artifacts around the cortical bone. Therefore, the interpretation of periosteal lesions using 3D UTE and 3D UTE FS requires caution.

Supplementary Materials

The Data Supplement is available with this article at https://doi.org/10.3348/kjr.2020.0640.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Acknowledgments

We extend special thanks to scientists and applicators in GE Healthcare, including Youngju Lee, Michael Carl, for developing and optimizing the 3D UTE sequence. We also deeply appreciate our MR technicians, including Gyangpyo Hong.

Author Contributions

Conceptualization: Yeo Ju Kim, Jang Gyu Cha. Data curation: Dae Joong Kim, Kun Hwang, Hun Kim. Formal analysis: Yeo Ju Kim, Jang Gyu Cha, Dae Joong Kim. Funding acquisition: Yeo Ju Kim. Investigation: Yeo Ju Kim, Dae Joong Kim, Kun Hwang, Hun Kim, Ju-Yong Park. Methodology: Yeo Ju Kim, Jang Gyu Cha, Dae Joong Kim, Kun Hwang. Project administration: Yeo Ju Kim. Resources: Yeo Ju Kim, Dae Joong Kim, Kun Hwang, Hun Kim. Software: Hyungseok Jang. Supervision: Yeo Ju Kim, Jang Gyu Cha. Visualization: Yeo Ju Kim, Dae Joong Kim, Kun Hwang, Hun Kim, Hyungseok Jang, Ju-Yong Park. Writing—original draft: Yeo Ju Kim, Hyungseok Jang. Writing—review & editing: Yeo Ju Kim, Hyungseok Jang.

ORCID iDs

Dae Joong Kim
https://orcid.org/0000-0002-7841-4153
Kun Hwang
https://orcid.org/0000-0002-1994-2538
Hun Kim
https://orcid.org/0000-0002-6296-9584
Jang Gyu Cha
https://orcid.org/0000-0002-3803-4850
Hyungseok Jang
https://orcid.org/0000-0002-3597-9525
Ju-Yong Park
https://orcid.org/0000-0002-5957-9526
Yeo Ju Kim
https://orcid.org/0000-0002-1783-8876

REFERENCES

1. Dwek JR. The periosteum: what is it, where is it, and what mimics it in its absence? *Skeletal Radiol* 2010;39:319-323
2. Reichert IL, Benjamin M, Gatehouse PD, Chappell KE, Holmes

J, He T, et al. Magnetic resonance imaging of periosteum with ultrashort TE pulse sequences. *J Magn Reson Imaging* 2004;19:99-107
3. Tyler DJ, Robson MD, Henkelman RM, Young IR, Bydder GM. Magnetic resonance imaging with ultrashort TE (UTE) pulse sequences: technical considerations. *J Magn Reson Imaging* 2007;25:279-289
4. Bae WC, Dwek JR, Znamirowski R, Statum SM, Hermida JC, D'Lima DD, et al. Ultrashort echo time MR imaging of osteochondral junction of the knee at 3 T: identification of anatomic structures contributing to signal intensity. *Radiology* 2010;254:837-845
5. Techawiboonwong A, Song HK, Leonard MB, Wehrli FW. Cortical bone water: in vivo quantification with ultrashort echo-time MR imaging. *Radiology* 2008;248:824-833
6. Ma L, Meng Q, Chen Y, Zhang Z, Sun H, Deng D. Preliminary use of a double-echo pulse sequence with 3D ultrashort echo time in the MRI of bones and joints. *Exp Ther Med* 2013;5:1471-1475
7. Chang EY, Du J, Chung CB. UTE imaging in the musculoskeletal system. *J Magn Reson Imaging* 2015;41:870-883
8. Bydder GM. Review. The Agfa Mayneord lecture: MRI of short and ultrashort T_2 and T_{2*} components of tissues, fluids and materials using clinical systems. *Br J Radiol* 2011;84:1067-1082
9. Lu A, Daniel BL, Pauly JM, Pauly KB. Improved slice selection for R2* mapping during cryoablation with eddy current compensation. *J Magn Reson Imaging* 2008;28:190-198
10. Rahmer J, Börnert P, Groen J, Bos C. Three-dimensional radial ultrashort echo-time imaging with T2 adapted sampling. *Magn Reson Med* 2006;55:1075-1082
11. Josan S, Pauly JM, Daniel BL, Pauly KB. Double half RF pulses for reduced sensitivity to eddy currents in UTE imaging. *Magn Reson Med* 2009;61:1083-1089
12. Johnson KM. Hybrid radial-cones trajectory for accelerated MRI. *Magn Reson Med* 2017;77:1068-1081
13. Gurney PT, Hargreaves BA, Nishimura DG. Design and analysis of a practical 3D cones trajectory. *Magn Reson Med* 2006;55:575-582
14. Du J, Bydder M, Takahashi AM, Carl M, Chung CB, Bydder GM. Short T2 contrast with three-dimensional ultrashort echo time imaging. *Magn Reson Imaging* 2011;29:470-482
15. Atkinson IC, Lu A, Thulborn KR. Characterization and correction of system delays and eddy currents for MR imaging with ultrashort echo-time and time-varying gradients. *Magn Reson Med* 2009;62:532-537
16. Bydder GM, Chung CB. Magnetic resonance imaging of short T2 relaxation components in the musculoskeletal system. *Skeletal Radiol* 2009;38:201-205
17. Duyn JH, Yang Y, Frank JA, van der Veen JW. Simple correction method for k-space trajectory deviations in MRI. *J Magn Reson* 1998;132:150-153
18. Jang H, McMillan AB. A rapid and robust gradient measurement technique using dynamic single-point imaging. *Magn Reson Med* 2017;78:950-962
19. Bakker CJ, Bhagwandien R, Moerland MA, Fuderer M. Susceptibility artifacts in 2DFT spin-echo and gradient-echo imaging: the cylinder model revisited. *Magn Reson Imaging* 1993;11:539-548
20. Reichenbach JR, Venkatesan R, Yablonskiy DA, Thompson MR, Lai S, Haacke EM. Theory and application of static field inhomogeneity effects in gradient-echo imaging. *J Magn Reson Imaging* 1997;7:266-279
21. Bydder M, Du J, Takahashi A, Shimakawa A, Hamilton G, Sinha S, et al. Chemical shift artifact in center-out radial sampling: a potential pitfall in clinical diagnosis. Proceedings of the 15th Annual Meeting of ISMRM; 2007 May 19-25; Berlin, Germany: ISMRM; 2007. p. 1811
22. Bisseret D, Kaci R, Lafage-Proust MH, Alison M, Parlier-Cuau C, Laredo JD, et al. Periosteum: characteristic imaging findings with emphasis on radiologic-pathologic comparisons. *Skeletal Radiol* 2015;44:321-338

 https://doi.org/10.3348/kjr.2020.0640