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Physiological assessment of in vivo human knee articular cartilage using sodium MR imaging at 1.5 T

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ABSTRACT

Osteoarthritis is a common joint disorder that is most prevalent in the knee joint. Knee osteoarthritis (OA) can be characterized by the gradual loss of articular cartilage (AC). Formation of lesion, fissures and cracks on the cartilage surface has been associated with degenerative AC and can be measured by morphological assessment. In addition, loss of proteoglycan from extracellular matrix of the AC can be measured at early stage of cartilage degradation by physiological assessment. In this case, a biochemical phenomenon of cartilage is used to assess the changes at early degeneration of AC. In this paper, a method to measure local sodium concentration in AC due to proteoglycan has been investigated. A clinical 1.5-T magnetic resonance imaging (MRI) with multinuclear spectroscopic facility is used to acquire sodium images and quantify local sodium content of AC. An optimised 3D gradient-echo sequence with low echo time has been used for MR scan. The estimated sodium concentration in AC region from four different data sets is found to be ~225 ± 19 mmol/l, which matches the values that has been reported for the normal AC. This study shows that sodium images acquired at clinical 1.5-T MRI system can generate an adequate quantitative data that enable the estimation of sodium concentration in AC. We conclude that this method is potentially suitable for non-invasive physiological (sodium content) measurement of articular cartilage.

1. Introduction

Osteoarthritis (OA) refers to a serious, painful and life-altering joint disease that will lead to failure of the synovial joint organ [1]. Worldwide prevalence estimates for symptomatic OA have reached 9.6% and 18% for men and women, respectively [2]. The progression of early OA might occur within 10 years of a major injury; meaning that if the case of injury does occur at a young age of 15, the OA may set in as early as age 25 [1].

Rather than any other synovial joint organs, OA more commonly occurs in the knee in which its main feature is able to be characterized by the gradual loss of articular cartilage (AC) [3]. Here, AC is a stiff yet flexible soft fibrous tissue found on the surface of end bones. At the tissue level (between 100 μm and 1 cm in scale), AC, as shown in Fig. 1, can be viewed as a solid homogeneous structure [4]. At the microscopic level, the molecular view of cartilage, meanwhile, is found to consist of various molecular compositions such as water, proteoglycan and collagen type II. In articular cartilage, the changes of such molecular compositions have been in use for detecting and monitoring the progression of OA at various stages.

It is reported that cartilage tissue contains water in the range of 60% to 80% and chondrocytes surrounded by extracellular matrix (ECM). The primary components of the extracellular matrix are type II collagen (5%–10% of total cartilage composition) and large proteoglycan (PG) molecule (10%–20% of total cartilage composition). All three components act together to provide a mechanical support (mechanical behaviour) of AC within a synovial joint [5].

At the very beginning, the disruption of the collagen fibril and network will release proteoglycan (PG) that results in a lesion on the superficial zone, tissue softening, fissures, and fibrillation and will increase in water content of the articular cartilage [3–5]. At early stage, these changes are detectable under a microscope, yet requiring an invasive procedure. At present, the accurate diagnosis of osteoarthritis is in general possible only when the disease is in a significant progression, and physicians can do little more than making a diagnosis of osteoarthritis based on a physical examination and history of symptoms.

Magnetic resonance imaging (MRI) has been widely used to provide an excellent anatomical detail of AC tissue and capabilities in quantifying a variety of compositional and functional parameters of AC [6]. In past, in order to measure the biochemical contents of AC

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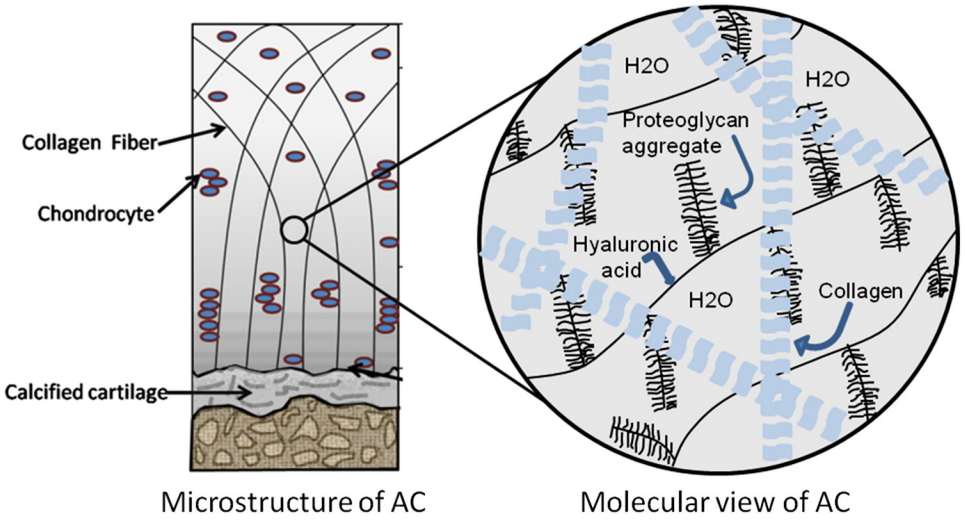

Fig. 1. Schematic representation of articular cartilage showing a solid homogeneous structure and molecular compositions at microscopic level.

that enables a physiological measurement, several MRI techniques such as T1rho (i.e., spin–lattice relaxation in the rotating frame) imaging, delayed gadolinium-enhanced MRI of cartilage (dGEMRIC), MT (magnetization transfer), diffusion tensor imaging, T_2 mapping and sodium MRI were used [7–9]. These techniques have been associated with a number of different biochemical contents of cartilage tissues such as T_2 mapping with water, T1rho with PG content, dGEMRIC with PG, MT with collagen content, diffusion tensor imaging with collagen orientation and sodium MRI with PG contents.

Loss of proteoglycan as the physiological changes in AC has been associated with the onset of OA and has demonstrated the decrease in PG over 40% [10] to 50% [11] in bovine articular cartilage. The changes of proteoglycan content in AC have been successfully measured using dGEMRIC [12] and sodium MRI [13] Techniques. In dGEMRIC protocol, gadolinium-diethylenetriaminepentaacetic acid (Gd-DTPA) contrast enhancement agent is injected in the body prior to scanning and subjects need to exercise for approximate 10 min and then, the imaging is performed after 2–3 h. This technique is time-intensive and needs contrast agent that, in turn, makes this method inconvenient [14].

The sodium MR signal can measure in PG concentration of AC [8]. Recently, the feasibility of sodium MRI of cartilage tissue has been demonstrated in in vivo human knee articular cartilage that was performed using a dual-tuned knee coil at 1.5-T clinical MRI [15]. For cartilage, due to the local sodium content in AC, a contrast agent is not required when using sodium (^{23}Na)-based MRI. However, sodium imaging requires a specialised RF coil as well as a high-field MRI machine to achieve the significant information on sodium signals. Research has shown that sodium concentration in cartilage could be measured significantly using sodium MR imaging at >3-T MRI [7,16]. However, considering that MRI Scanner with >3 T is only available in certain clinics and academic research centres that limits the use of sodium imaging methods. Thus, this study has been conducted toward measuring physiological (sodium content) parameters of AC using sodium MRI at 1.5 T.

2. Sodium MRI of articular cartilage

2.1. Sodium MR imaging

In clinical practice, hydrogen (^{1}H) nuclei are used mostly to perform MR scan due to its abundant amount in human body [17]. It is well known that human tissue and organs have different amount of water content which changes according to the pathological process of the disease. In MR images, the distribution of such water content is reflected as a tissue contrast that, in turn, could assist clinicians in diagnosing the disease. In addition to hydrogen nuclei, other nuclei such as sodium (^{23}Na), fluorine (19 F), and carbon (^{13}C) can be used to perform MR scan as well [17,18].

For the sodium imaging, sodium MRI requires a four times stronger gradient to obtain the same resolution image as proton images due to its four times lower sodium gyromagnetic ratio (γ). In human body, sodium ions are much lower than those of hydrogen that results in a low sensitivity (~9.2%) of sodium imaging compared to proton MRI. In vivo water proton concentration is approximately 360 times larger than in vivo sodium concentration. Those factors above in consequence influence the sodium signal that results in 4000 times smaller sodium signals during sodium MR imaging compared to proton MRI [19]. For this, visualizing anatomy of any tissue using sodium MR imaging, somehow, becomes challenging. However, it has been found that ^{23}Na imaging is more beneficial for the imaging of pathological conditions for providing quantitative results in which proton MRI may not be able to do so.

2.2. Sodium imaging of articular cartilage

At the very beginning of articular cartilage degeneration, depletion of proteoglycan has resulted in a reduction of glycosaminoglycan (GAG) contents in cartilage. It has been investigated that the GAG contents are correlated with the fixed charge density (FCD) of cartilage [10]. GAGs are negatively charged and maintain the amount of FCD in AC while FCD of cartilage is counterbalanced by the sodium ions. Thus, the loss of PG (hence GAG and FCD) will result in the releasing of the positively charged sodium ions from the cartilage. Therefore, sodium MRI shows the possibility to perform MR scan for cartilage imaging.

For the cartilage imaging, sodium MRI shows promising results because sodium content in surrounding tissue in knee joint is low (<50 mM) that can produce a high-contrast cartilage region in sodium images. In addition, it is highly specific to PG contents and there will be no requirement of exogenous contrast agent to be injected in the body prior to MR scan [19]. The sensitivity of sodium MR imaging is adequate for detecting small changes in proteoglycan content on the order of 5% [20].

Shapiro and co-workers [20] measured the sodium concentration in normal human patellar AC that ranges ~240 to 260 mM at 4-T MRI scanner. These results were then validated by converting sodium

concentration into FCD and compared to FCD values measured using dimethylmethylene blue PG assays. Both methods used to measure FCD show similar values. Similarly, the mean values of FCD measured were found to be −182 mmol/l ± 9 in a healthy human cartilage and ranging from −108 to −144 mmol/l in symptomatic subject's cartilage which shows a significant decrease in the FCD values that have been measured at 4-T MRI. In the same study, sodium concentration measured from nine healthy volunteers was at 254 mmol/l ± 7 (standard error) [10]. The above studies performed on a high-field (>3 T) MRI scanner show the feasibility of sodium imaging of AC. However, as already previously mentioned, the availability of MRI scanner with >3 T is rare in most of the clinics and limits the clinical aspects of the above studies.

3. Materials and methods

3.1. Imaging experiment setup

All scans were performed using a 1.5-T clinical MR system equipped with a multinuclear spectroscopy facility (Siemens Medical Solutions, Erlangen, Germany) at Magnetic Resonance Bavaria (MRB) Research Centre, Wurzburg, Germany. Fig. 2 illustrates a schematic representation of experimental setup. In the experiment, a radiofrequency (RF) coil (Quadrature polarized, volume dual-tuned knee coil "^{23}Na/^{1}H" by Rapid Biomedical GmbH, Germany as shown in Fig. 3) equipped with proton (^{1}H) and sodium (^{23}Na) channel was used to scan phantoms and human subjects. In the coil, proton and sodium channels were tuned at 63.6 and 16.8 MHz, respectively. For the absolute measurement of sodium content in AC, a calibration marker (a plastic tube with 300 mmol/kg sodium concentration as shown in Fig. 4) was placed next to the human knee as a sodium reference. Once the scan was performed, MR data were collected and stored into a workstation for the need of further analysis.

3.2. Data acquisition

Prior to performing MR scan on human subjects, ^{23}Na/^{1}H coil was tested on phantoms (standard Siemens phantom containing 85.5 mmol/l sodium concentration) in which the performance of the coil was evaluated by measuring a signal-to-noise (SNR) ratio obtained in the MRI scans. SNR in phantom images is measured as the mean signal intensity in the region of interest (ROI) in phantom area divided by the standard deviation of ROI from signal-free area [21].

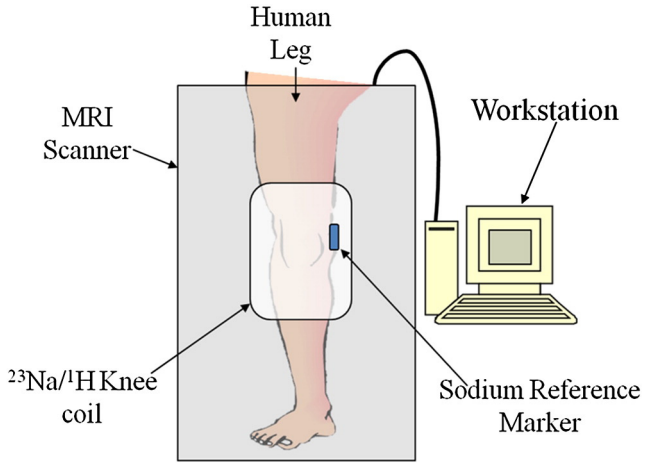

Fig. 2. Experimental setup for MR imaging: consisting of acquisition devices (MR scanner with multinuclear capabilities and ^{23}Na/^{1}H knee coil), subject, calibration reference (sodium reference marker) and acquisition unit (collection and storage).

Fig. 3. Dual-tuned knee coil (^{23}Na/^{1}H) equipped with proton channel (^{1}H-tuned at 63.6 MHz) and sodium channel (^{23}Na-tuned at 16.8 MHz).

After the successful testing of dual-tuned knee coil, sodium imaging of the knee and phantoms was performed using 3D gradient-echo sequence with the following parameters: repetition time/echo time (TR/TE) = 11.4/4.0 ms, flip angle = 60°, image resolution = 2.81 × 2.81 × 8 mm^3, and total acquisition time was within ~30 min). In addition to sodium imaging, proton imaging was also performed using MEDIC (multi-echo data imaging combination) 3D sequence (TR/TE = 37/20 ms, flip angle = 8°, image resolution = 0.47 × 0.51 × 1.5 mm^3, and total acquisition time ~5 min). Five different knees of human subjects (unknown diagnosis) were then scanned using the above MRI scan protocol. Here, both sodium and proton MRI data of all five scans were collected using an external storage media and stored into a window-based workstation for the further processing and analysis.

3.3. Measurement of sodium concentration

The sodium images of human in vivo knee are acquired using the quadrature polarized, volume dual-tuned knee coil "^{23}Na/^{1}H" with 3D gradient-echo imaging sequence. The imaging parameters are optimized to give an average signal-to-noise (SNR) of around 8.2 in cartilage region. Although, the coil design allows us to image a large FOV region in human knee with significant SNR, an RF field inhomogeneity was observed during the experiments due to a decrease in sensitivity of the coil as a function of distance from transmit coils. First, B1 (RF) inhomogeneity is corrected in sodium images using the fiduciary markers as shown in Fig. 5. In order to

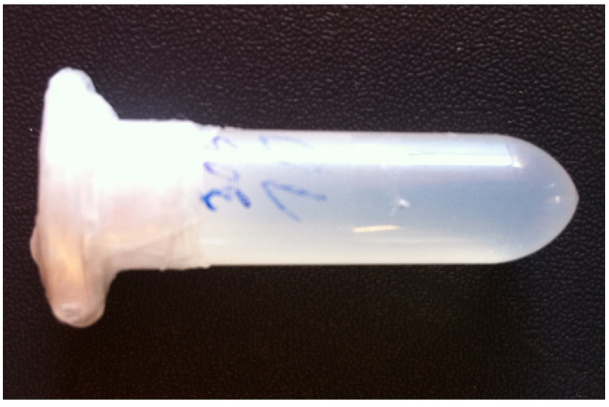

Fig. 4. Calibration reference with sodium concentration of 300 mmol/l.

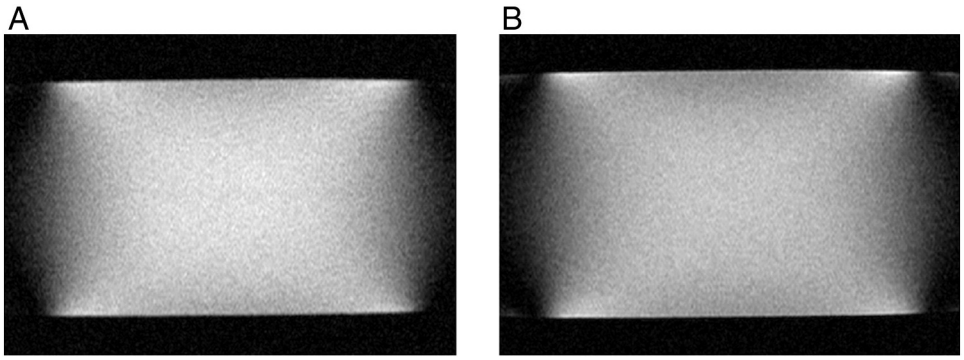

Fig. 5. Sodium images of phantom (A) before correction of RF homogeneity and (B) after correction of RF homogeneity.

image in vivo sodium knee images, a similar correction is applied that gives a homogeneous sodium signal in acquired images.

In order to measure the absolute sodium content of articular cartilage from the sodium knee images, a calibration marker (a plastic tube filled with 300 mmol/l sodium concentration) was placed next to the human knee as a sodium reference. The sodium concentration was determined in the AC ($[Na]_{AC}$) region of ^{23}Na MRI images as the ratio of the mean ^{23}Na signal intensities (S_{Na}) in a cartilage region to the sodium signal from the reference marker ($S_{Na\ ref}$) of 300 mmol/l sodium concentration ($[Na]_{ref}$) using Eq. (1) as reported in earlier studies [22]:

$$[Na]_{AC} = \frac{S_{Na}}{S_{Na\ ref}}[Na]_{ref} \quad (1)$$

where $[Na]_{AC}$ is the sodium concentration to be measured in cartilage region, S_{NA} is the mean signal intensities determined in cartilage region, $S_{Na\ ref}$ is the mean signal intensities determined in a sodium reference region and $[Na]_{ref}$ is the known identified sodium concentration in the sodium reference.

The sodium signal intensities of both reference marker region and cartilage from the sodium images are extracted by following the steps outlined in flow diagrams as shown in Figs. 6 and 7 for a reference and for a cartilage, respectively. The original format of DICOM (digital imaging and communications in medicine) is used to preserve the maximum information.

Measurement of sodium signals in reference and cartilage regions is performed within a single data set. The first few slices of the data set are used to extract the sodium signal intensities in the reference marker region and the rest of the slices were utilized for cartilage region. A post-processing program is developed for the selection region of interest (ROI) of reference marker and the extraction of sodium pixels. In order to select the reference marker ROI, an edge detector with an optimal threshold value (0.5) is applied to extract all the available objects within the image. The threshold value is selected based on the number of experiments performed for different sequences slices. Furthermore, all the connected components in the image are selected and property of image region as area less than 100 pixels is measured that results in a single object as reference marker ROI in the image. In this way, only the reference region as ROI is selected which is further converted into a phantom mask. Once the mask is generated, a number of pixels existing in the mask were extracted followed by the calculation of mean signal intensities.

For sodium signal intensities in cartilage region, a sodium image sequence is further processed without the first two and last two slices to preserve the maximum accuracy. Here, since the slice is used for the extraction of reference region intensities from the same sequence, the pixel information obtained during the extraction of reference region is used to extract the sodium pixels in all slices containing the cartilage region. In the same manner as before, ROI is

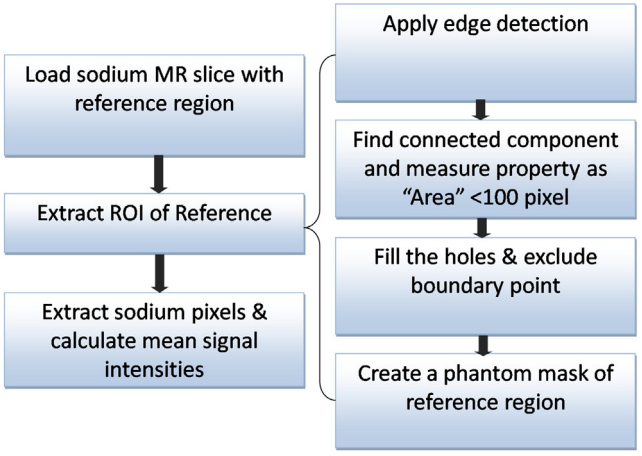

Fig. 6. Flow diagram showing steps in sodium signal intensities extraction in sodium reference.

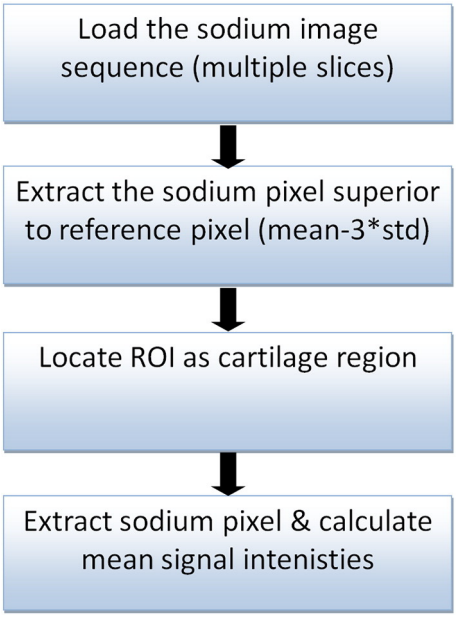

Fig. 7. Flow diagram showing steps in sodium signal intensities extraction in sodium MR sequence.

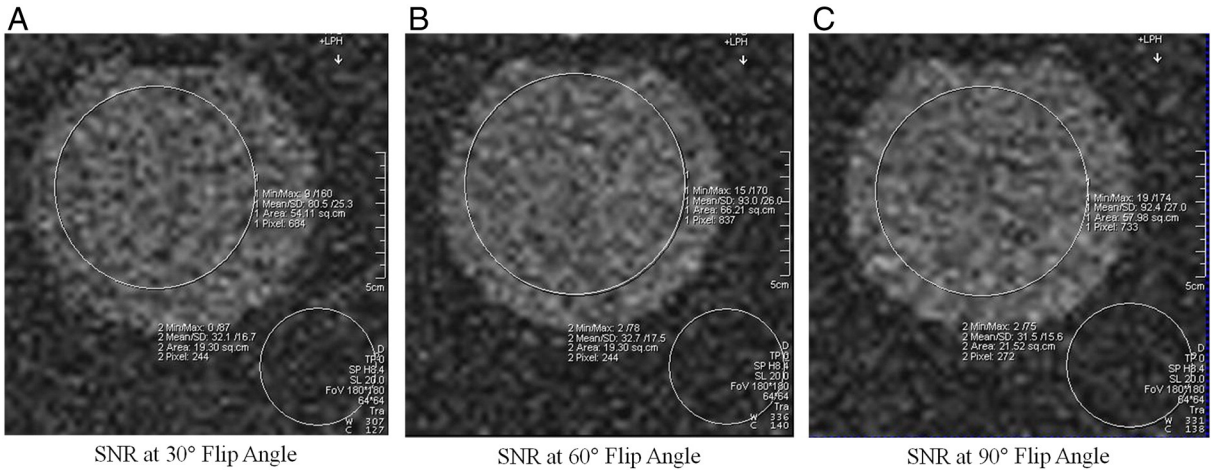

Fig. 8. SNR measurement in standard phantom (85.5 mmol/l sodium concentration) images at 30°, 60° and 90° of flip angle.

located in sodium sequence slices followed by the extraction of number of pixels and calculation of mean signal intensities.

4. Results

4.1. SNR measurements

SNR in the phantom (standard Siemens phantom containing 85.5 mmol/l sodium concentration) images is measured as the mean signal intensity in the region of interest (ROI) in a phantom area divided by the standard deviation of ROI from a signal-free area as shown in Fig. 8. SNR values measured at 30°, 60° and 90° of flip angle from three different experiments are listed in Table 1.

Essentially on the account of both the difference in the amount of water protons and sodium ions in the body and the low gyromagnetic ratio at 1.5 T, the SNR of ^{23}Na MRI, as reported, becomes much lower than that of ^{1}H MRI. The measured SNR, however, shows the adequacy of sodium imaging at 1.5 T. We have also measured the SNR values from the sodium images of in vivo human knee as the mean signal intensity in the ROI (cartilage region) divided by the standard deviation of ROI selected in a signal-free area [21]. Likewise, SNR was calculated for the sodium reference marker region from the sodium knee images. Both the mean signal intensities and the standard deviation values are extracted from the sodium images using custom routines programmed in MATLAB®. Table 2 shows the extracted values from different regions in both the sodium image of in vivo human knee and the measured SNR.

Recently, Moon and co-workers [23] in their work reported that the sodium concentration in healthy articular cartilage is 204.9 ± 24 mmol/l that matches the physiological values reported earlier. In our study, SNR values measured from standard Siemens phantom (sodium concentration −85.5 mmol/l) image online on MRI machine and cartilage (sodium concentration ~180 to 260 mmol/l, depending on the region of cartilage) region in sodium MR image using offline post-processing are approximately 4.8, and 8.2, respectively. The measured SNR values corresponding to the physiological values are somewhat lower in the cartilage region compared to the standard phantom mainly due to the offline post-processing method performed using a routine program. Secondly, the SNR in cartilage region is measured from a single slice that may contain low sodium signals compared to background noise in the image. However, the SNR measured from cartilage region is comparable to the values (7.3–11.3) reported earlier that shows adequacy of physiological imaging of cartilage [24].

4.2. MRI data acquisition

After the successful testing of the coil, MRI data from human subjects were acquired from five subjects using the protocol defined earlier. The acquired data consisted of the proton and sodium knee MRI images in the original DICOM format. Fig. 9 shows the MRI images acquired using a dual-tuned knee coil at 1.5-T MRI scanner.

For the sodium content measurement, we have used only sodium knee images. However, the acquired proton image sequence was kept in a database for further processing of a morphological assessment. In the data set acquired from five different subjects, one of the data set consisted of an artifact as shown in Fig. 9(D). This might occur due to the improper positioning of the subject knee in the coil during MR scan. Dual-tuned knee coil (^{23}Na/^{1}H) is a quadrature polarized volume coil that is detachable and an improper attachment of the coil may cause the radio frequency (RF) leak that will result in an artifact in the image. Hence, only data from four subjects were used for the measurement of sodium concentration in AC.

In addition to the sodium images, the proton images of the same subjects, as shown in Fig. 9(A), were acquired using MEDIC (multi-echo data imaging combination) 3D sequence in the same position. The proton images, in this case, are acquired to assess the morphology by registering them with the sodium images in the same plane. As shown in Fig. 10, we were able to fuse the proton and the sodium images.

For the fusion, multi-view fusion method is applied as the images are acquired from the same modality and same plane but

Table 1
SNR measurements in phantoms at different flip angle.

FA	MSI in $ROI_{phantom}$	SD in ROI_{air}	SNR
FA-30°	80.5	16.7	4.82
FA-60°	93	17.5	5.31
FA-90°	92.4	15.6	5.92

FA, flip angle; MSI, mean signal intensity, SD, standard deviation.

Table 2
SNR measurement at different regions in in vivo sodium images.

Region	MSI	SD in ROI_{air}	SNR
Cartilage	148.1061	17.9526	8.24
Sodium reference	147.1154	11.7934	12.47

MSI, mean signal intensity; SD, standard deviation.

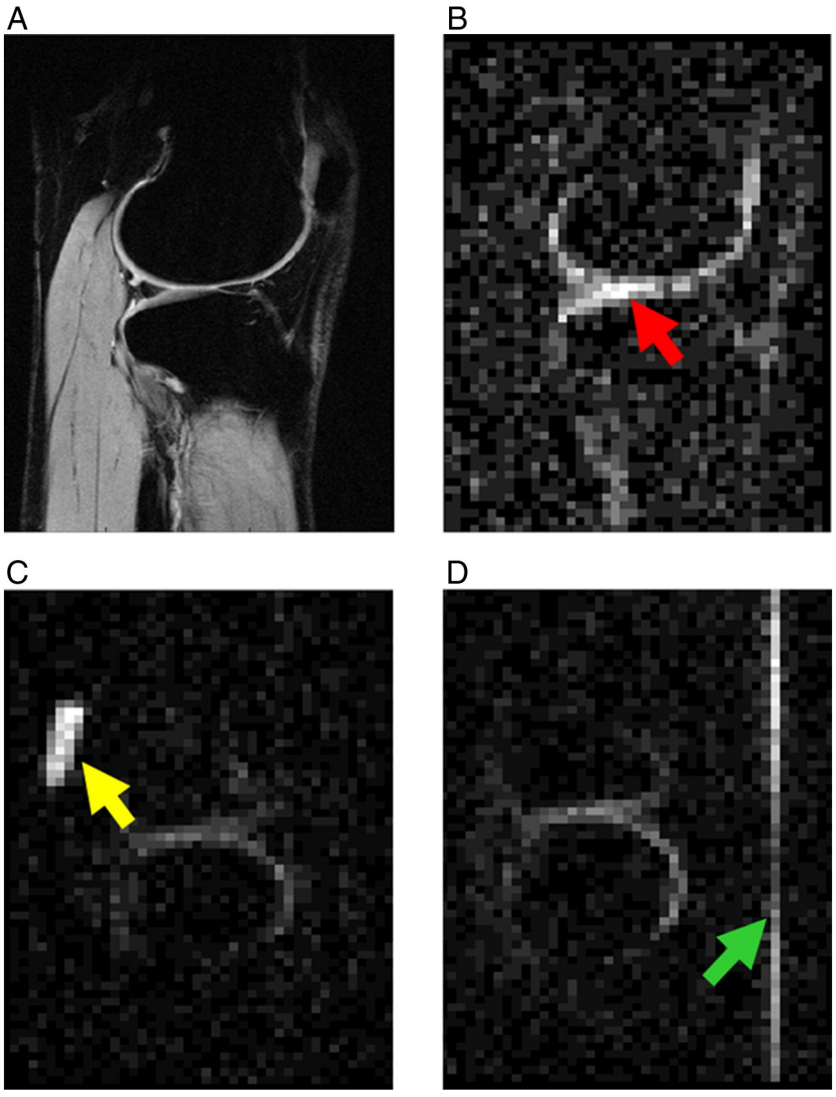

Fig. 9. (A) High-resolution proton image. (B) Sodium image showing high contrast on cartilage region (red arrow). (C) Sodium image showing high contrast in phantom region (yellow arrow). (D) Sodium image with artifact (green arrow).

in different conditions. There are two challenges occurring while fusion of sodium and proton images is performed: (1) MR images acquired consists of two different matrix sizes with same field of view (FOV) and (2) different number of slices acquired in each data set. Thus, location of sodium slices in the FOV was selected with respect to the corresponding slices in the proton sequence. Secondly, sodium region from all slices were extracted using the method developed by Fadzil et al. [15]. Once the sodium region is extracted from all the slices in sodium sequence, re-sampling using cubic spline interpolation is applied followed by the normalization of slices. All re-sampled slices of sodium extracted region were then merged using a weightage coefficient (0.5) with corresponding proton slices. The information available in the fused proton and sodium image, could later be used for the morphological measurement of early osteoarthritis. For an example, cartilage boundaries from the set of fused MRI slices can be extracted more accurately as fused images contain more information on cartilage region. Extracted cartilage boundaries in fused images will provide 3D surface points to reconstruct 3D models of articular cartilage that may enable the measurement of accurate cartilage thickness on load wearing sites (different compartments) as well as inner and outer surfaces (different zones).

4.3. Measurement of sodium concentration

Sodium signal intensities in the reference and the cartilage region were extracted from the sodium images as defined in Figs. 6 and 7, respectively. Fig. 11, meanwhile, shows the extraction of sodium pixels to measure the signal intensities in the reference and the cartilage region. The mean sodium signal intensities calculated from the sodium reference (Fig. 11D) and articular cartilage (Fig. 11 H) in the sodium MRI image were 199 and 168 for 22 and 81 pixels, respectively representing a homogeneous and intense sodium signal in both reference and AC.

The developed protocol was applied on sodium MRI sequence comprising 12 slices in each data set. In the processing, only 8 slices are used to extract the pixels containing sodium information because slice numbers 1, 2, 11 and 12 do not represent the cartilage and sodium reference region. Slice numbers 1, 2, 11 and 12 were excluded to preserve the accuracy in the measurement. Fig. 12 shows the extracted cartilage region representing sodium signal values from a single data set of the sodium knee images.

The extracted mean sodium signal intensities in the sodium reference and cartilage region were used to determine the sodium concentration in a knee cartilage. The sodium mean intensities

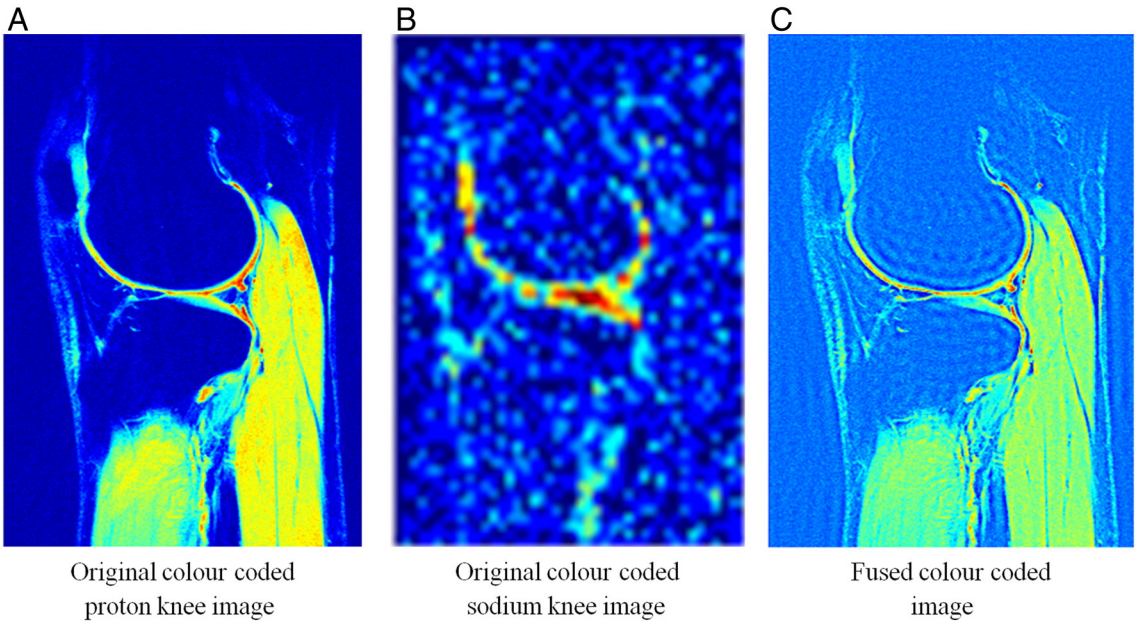

Fig. 10. Fusion of proton and sodium knee MR images: (A) original color-coded proton knee image, (B) original color-coded sodium knee image and (C) resulting fused-knee image.

measured from a reference marker as well as in cartilage region for four different data sets are reported in Table 3. Mean signal intensities measured from the reference and cartilage region were then used to measure sodium concentration using Eq. (1).

The results from this study show that the sodium concentration measured in AC was relatively similar to that reported in earlier studies [10]. In addition, numbers of pixels measured in four different reference markers are 21, 23, 22 and 21, which shows a good reproducibility in our method.

5. Discussion

In a clinical practice, hydrogen (^{1}H) nuclei are used mostly to perform MR scan. In addition to proton-based MRI, sodium (^{23}Na)-based MR scan can be used to image the AC as it contains high sodium. Current research in MRI hardware is revolving around the development of dual-tuned (^{1}H/^{23}Na) coil that can excite both hydrogen and sodium nuclei using a single coil. However, the functionality of such hardware device is challenging at 1.5-T MRI

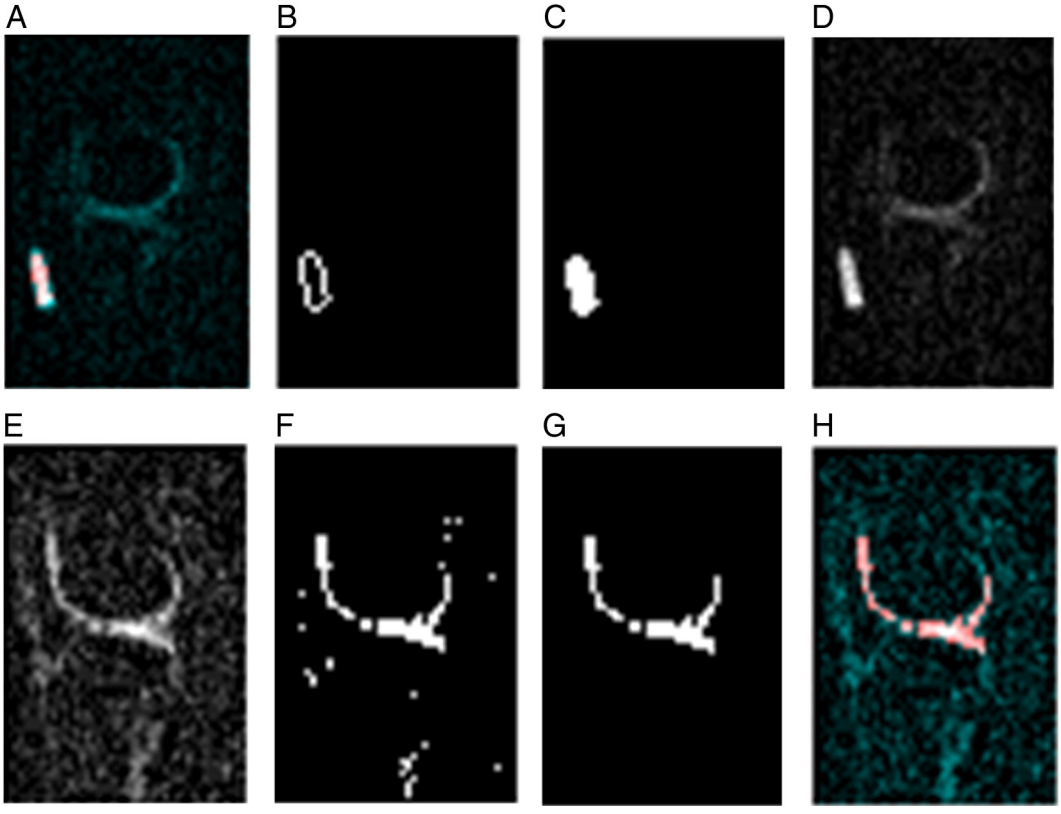

Fig. 11. Sodium pixel extraction to calculate the mean signal intensities from reference and sodium knee cartilage.

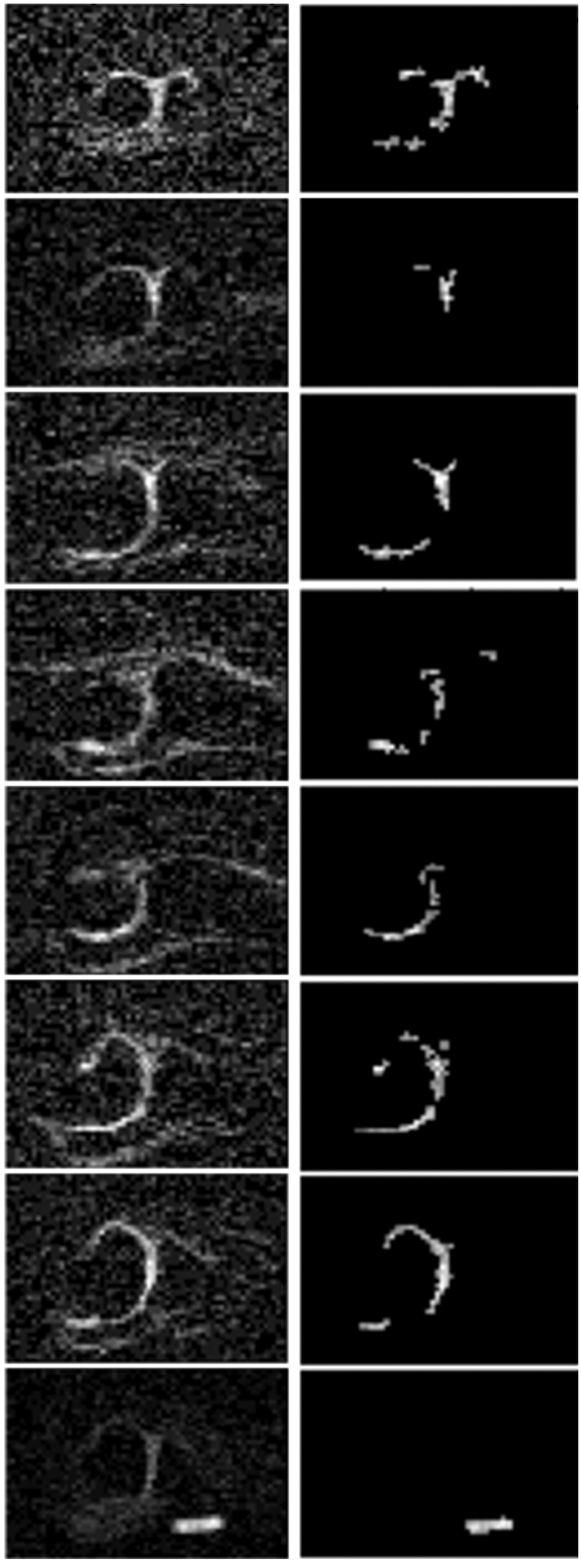

Fig. 12. Extraction of sodium pixels in the cartilage region from slices of sodium data set: First row represents the original sodium sequence slices and second row represents the extracted sodium pixels in the same sequence.

Table 3
Sodium measurement from different data sets.

DS	Sodium reference		Cartilage region		Sodium concentration
	NOP	MSI	NOP	MSI	
DS 1	21	187.98	122	129.75	207.07 mmol/l
DS 2	23	189.13	62	159.26	252.61 mmol/l
DS 3	22	199.77	98	143.54	215.55 mmol/l
DS 4	21	189.65	189	143.57	227.10 mmol/l

DS, data set; NOP, number of pixels, MSI, mean signal intensity.

scanner due to both the lower gyromagnetic ratio (γ) and the low sensitivity of sodium imaging. In consequence, the less the sodium signal is, the lower the resolution in sodium images will be. However, it is reported that the sodium images of a patellar cartilage acquired at 3-T MRI with an acceptable SNR in the range of 7.3 to 11.3 for high resolution and standard resolution respectively are clinically useful [24]. In this study, we managed to acquire the sodium images of articular cartilage at 1.5 T with an SNR value of 8.24 in which the quality of images is acceptable to be in use in a clinical practice. The visual interpretation of such images may not provide any significant information to detect a number of morphological changes in a degenerative AC. However, the measurement of quantitative values yields the valuable information in detecting changes in physiology, in particular PG content changes in the degenerative AC.

In this work, the sodium concentration of AC was measured to evaluate the feasibility of a sodium imaging and quantification at 1.5-T MRI. Some earlier studies were successfully conducted on in vivo and in vitro sodium imaging at >3 T and significant changes were found in the samples of degenerative AC compared to that of normal AC. The results obtained from this study show that the sodium concentration measured from four data sets (estimated sodium concentration ~225 ± 19 mmol/l) with a coefficient of variation (CV) of 8.4% is similar to the values reported earlier for a normal human articular cartilage. In addition, we have observed that our method in calculating the signal intensities (used to measure sodium concentration) shows a good reproducibility now that the numbers of pixels calculated for unique reference region in sodium images of four different data sets were almost similar. However, there are few limitations of this study, such as the fact that reproducibility of test–retest scanning was not performed, which may provide significant outcomes in measuring the sodium concentration for the same subject. Similarly, the subjects scanned during the experimental phase were unknown. The sodium concentration values measured from the articular cartilage of known diagnosis (e.g. Normal and Grade 1 or 2 OA patients) may provide some differences in the quantitative values.

6. Conclusion

In this work, the feasibility of imaging and quantification of local sodium content of AC using sodium MRI at less than 3-T clinical MR systems has been investigated. Experiments were conducted using a dual-tuned knee coil ($^{23}Na/^{1}H$) at 1.5-T clinical MRI scanner.

The estimated sodium concentration in the AC region from four different data sets is found to be ~225 ± 19 mmol/l, which matches the values that have been reported in the literature. This study shows that sodium images acquired at clinical 1.5-T MRI system can generate an adequate quantitative data that enable the estimation of sodium concentration in AC. We conclude that this method is potentially suitable for non-invasive physiological (sodium content) measurement of articular cartilage.

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