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Stiffness imaging of the kidney and adjacent abdominal tissues measured simultaneously using magnetic resonance elastography (MRE)

Sabine F. Bensamoun^{a,*}, Ludovic Robert^b, Gwladys E. Leclerc^a, Laëtitia Debernard^a,
Fabrice Charleux^b

^aBiomechanics and Bioengineering Laboratory, UMR CNRS 6600, Université de Technologie de Compiègne, Compiègne, France

^bACRIM-Polyclinique Saint Côme, Compiègne, France

* Corresponding author. Université de Technologie de Compiègne (UTC)
Centre de Recherches de Royallieu Laboratoire de Biomécanique et Bioingénierie,
UMR CNRS 6600, Rue Personne de Roberval, BP 20529
60203 Compiègne cedex, France
Tel.: +33 3 44 23 43 90
E-mail address: sabine.bensamoun@utc.fr (S.F. Bensamoun)

ABSTRACT

To date, non-invasive methods to detect kidney malignancies and mild tumors remain a challenge. The purpose of this study was to establish the proper imaging protocol to determine kidney stiffness and its spatial distribution within the various kidney compartments such as the renal sinus, medulla, and cortex. Here, we have used magnetic resonance elastography (MRE) along with coronal oblique acquisition to simultaneously measure kidney stiffness in comparison with other tissues including the liver, spleen, and psoas.

Keywords: MRE technique; Kidney; Stiffness

INTRODUCTION

Malignant tumors and other tissue abnormalities are often characterized by stiffness that differs markedly from surrounding normal tissue. Thus, practical methods for imaging elasticity of soft tissues might have significant diagnostic value. New non-invasive imaging diagnostic methods, such as transient elastography was developed to quantitatively assess liver fibrosis [1,2]. This technique analyzes wave velocity propagation which increases with the level of fibrosis [3] allowing for the establishment of a stiffness data base. In parallel to this ultrasound method, a magnetic resonance imaging technique for visualizing the propagation of acoustic shear waves has been developed (called MRE: Magnetic Resonance Elastography) [4]. Human studies have demonstrated that it is possible to apply MRE to quantitatively image the stiffness of healthy and pathological soft tissues such as skeletal muscles [5,6], gray and white matter in the brain [7], breast [8] and liver [9,10].

Recently, the stiffness of other abdominal organs was investigated and Yin et al. [11] have demonstrated the feasibility of the MRE technique to measure the stiffness of the pancreas, kidney, spleen, and small intestine. In the same way, Talwalkar et al. [12] showed the ability of the MRE technique to measure the spleen stiffness in order to analyse the effects of chronic liver disease on the spleen. Interestingly, they demonstrated an increase in spleen stiffness in patients with chronic liver disease.

The purpose of this study is to establish the proper imaging protocol to determine kidney stiffness using MRE and to simultaneously measure other tissues stiffness's such as liver, spleen and psoas.

MATERIALS AND METHODS

Participants

Eleven volunteers (6 women and 5 male) without kidney abnormalities and no prior history of renal disease underwent a MRE test. This study has been approved by the institutional review board and informed consents were obtained from participants.

Development of MRE protocols for kidney stiffness imaging

Two different protocols were investigated in order to obtain the best method for measuring the kidney stiffness using Magnetic Resonance Elastography. For each method, a gradient-echo sequence was used and parallel slices with a thickness of 10 mm were prescribed.

In the first protocol, an axial plan was performed in order to select an axial slice containing the two renal parenchymal (Fig. 1a), taking care to avoid the renal sinus. This acquisition targets the superior part of the kidney as well as the liver tissue.

In the second protocol, the objective was to realize a coronal oblique plan going through the two renal parenchymal and the liver tissue (Fig. 2a). We placed the scan plan between the cortex and the medulla in order to avoid the renal sinus and to visualize the postero-superior part of the kidney.

Experimental Setup for Magnetic Resonance Elastography (MRE) technique

The subjects lay supine in a 1.5T Signa HDx MRI (General Electric, Milwaukee, WI) and the center of a cylindrical acoustic driver (diameter: 16cm) was placed at the same level of the diaphragm and positioned in contact with the rib cage. The body coil was used and the acoustic driver had a long hose connected to a large active loudspeaker. This system created time varying pressure waves propagating shear waves within the abdomen at 60Hz.

MRE images were collected with a motion-sensitized gradient echo sequence, collected at four time offsets (phase offsets) between the start of the motion and the motion-encoding gradients, using a single number of gradients. Two offsets were recorded in a row and during this acquisition the subjects held their breathing to avoid the motion of the kidney caused by the displacement of the diaphragm. The scan time recorded for 2 offsets was 16s. Then during the 2 remaining offsets it was very important that the apnea was maintained at the same level due to the smaller structure of the kidneys compared to the larger hepatic tissue, involving a very accurate placement of the scan plan and a good execution of the instruction.

The acquisition matrix was 256 x 64 (which was interpolated to 256 x 256), the flip angle was 30°, the field of view was between 34 cm and 48 cm in function of the morphology of the subject, the received bandwidth was 15.63 kHz, the frequency direction was R/L and the SNR was 100%. The TR was 100 ms and the TE corresponded to the minimum echo time (26.8 ms) that allowed for motion encoding.

Image Processing and Data Analysis

In the axial and coronal oblique images, MRE provides anatomical images of the kidneys and liver tissue (Fig. 1a, Fig. 2a) as well as phase images (Fig. 1b, 2b) showing the shear wave displacement within abdominal tissues. A map of the shear modulus (μ) was generated from the wave displacement image using the Linear Frequency Estimate (LFE) algorithm [13] providing a spatial distribution of the kidney's stiffness (Fig. 1c, 2c). Assuming that the tissue

is locally homogeneous, regions of interest (ROI) were placed around the target tissues (kidneys) and around adjacent tissues such as liver, spleen and the psoas muscle in order to also measure their stiffnesses. Repeatability of MRE acquisitions was done on each subject, the same day but at different times.

Statistical Analysis

Paired student's t-tests were performed with the software Statgraphics 5.0 (Sigma Plus, Maryland, USA) to compare the shear stiffness of the different abdominal tissues (kidney, liver, spleen, psoas). The level of significance was set at $P < 0.05$.

RESULT

The axial phase image (Fig. 1b) revealed a larger wavelength propagated within the right kidney compared to the liver tissue, leading to a significantly higher shear modulus for the kidney ($\mu_{\text{kidney}} = 4.12 \pm 0.24$ kPa) compared to the liver ($\mu_{\text{liver}} = 2.07 \pm 0.25$ kPa) (Fig. 1c). Coronal oblique images (Fig. 2c) provided similar stiffnesses for the kidney ($\mu_{\text{kidney}} = 4.32 \pm 0.59$ kPa) and liver ($\mu_{\text{liver}} = 2.27 \pm 0.19$ kPa). In addition, the stiffnesses of the spleen (4.75 ± 0.70 kPa) and psoas muscle (2.60 ± 0.25 kPa) were measured with the coronal plan, and we found that the shear modulus of the spleen and psoas were in the same range as the kidney and the liver, respectively.

The cartography of the shear modulus (Fig. 3) obtained for the right kidney revealed the different structures (renal sinus, medulla and cortex) located within the kidney. A gradient of stiffness was found corresponding to an increase in stiffness from the cortex to the renal sinus. Indeed, the renal sinus revealed a higher significant ($P < 0.05$) stiffness (6.78 ± 0.10 kPa) than the medulla (5.46 ± 0.48 kPa) and the cortex (4.35 ± 0.32 kPa).

The volume of the kidneys is smaller on the axial images and it is therefore difficult to anatomically image both kidneys in their totality, inducing only one measurement of stiffness for a single kidney. No significant difference of stiffness was detected between the right and left kidney through the coronal image.

DISCUSSION

The structures of the kidney are characterized with MRI imaging but biopsies remained the method used by clinicians to depict kidney pathologies even though it is a cause of complications and risks for the patients. Thus, there is a need to use a non-invasive method allowing for the quantification of stiffness pathology to identify kidney abnormalities including cancer and other pathologies such as glomerulonephritis.

Thus, the goal of the present study was to establish the proper protocol for imaging and establishing a kidney stiffness data base using MRE. To the best of our knowledge, this study is the first to assess the stiffness measurement of kidneys with a coronal oblique plan. This scan plan presents several advantages such as a larger field of view of the kidney section, allowing for an accurate identification of small damages, which may be located all over within the kidney. In addition, the present study is the first to show the strong sensibility of the MRE technique to represent the spatial distribution of the shear modulus which has been correlated with the structural composition of the kidney. However, though the use of the axial plan, it was not possible to establish a correlation between the structural and functional properties of the kidney (Fig. 1c). This information is of great importance for the characterization of kidney abnormalities present in the renal sinus, medulla or within the cortex.

Moreover, in the case of kidney cancer, it is also importance to monitor other tissues surrounded the pathological one. The coronal oblique plan allowed for the stiffness

measurement of several such tissues. In the same way, axial plan also allows for the visualization of other adjacent tissues stiffness of the kidney, but to the detriment of the spatial distribution of the stiffness measured within the various kidney compartments may be due to their smaller volume [11] through the axial plan. The liver stiffness measured in the axial and coronal oblique images were in agreement with the literature [9] as well as for the spleen stiffness [12]. The spleen and kidney exhibits higher stiffness than the liver due to their structure. There is little kidney stiffness data available in the literature [14], and Yin et al. [11] is the only study which has demonstrated the feasibility of the MRE technique to assess abdominal tissues stiffnesses through an axial plan. The comparison of kidney stiffness revealed similar data. However, the present study goes further in the kidney characterization and demonstrates a higher stiffness for the medulla compared to the cortex. Indeed, medulla is composed of different renal parenchyma resulting in a harder tissue than the cortex. Psoas is a skeletal muscle, having the same muscle fiber orientation as the vastus medialis (VM) muscle, and had a similar stiffness as the VM in a relaxed condition [5]. This result demonstrates the sensitivity of the MRE technique to provide new stiffness insights to characterize back muscles.

This study demonstrates that MRE technique could be a potential clinical tool for the characterization of renal damage in order to detect malignant and mild tumors.

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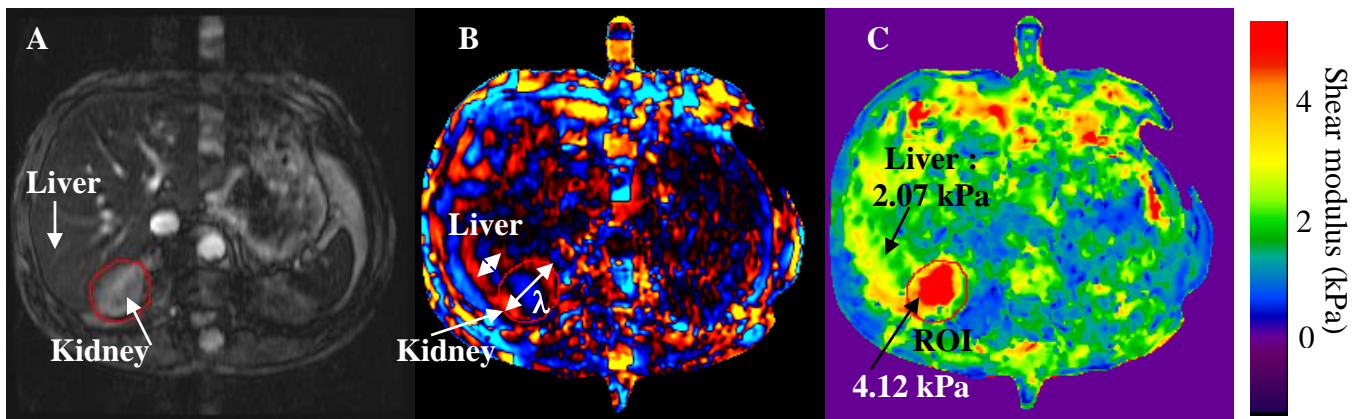


Fig. 1. A : Anatomical image of the liver and kidney trough an axial plan. B: Phase image showing a larger wave length (λ) inside the kidney compared to the liver. C: Cartographies of shear modulus with a region of interest (ROI) placed around the kidney.

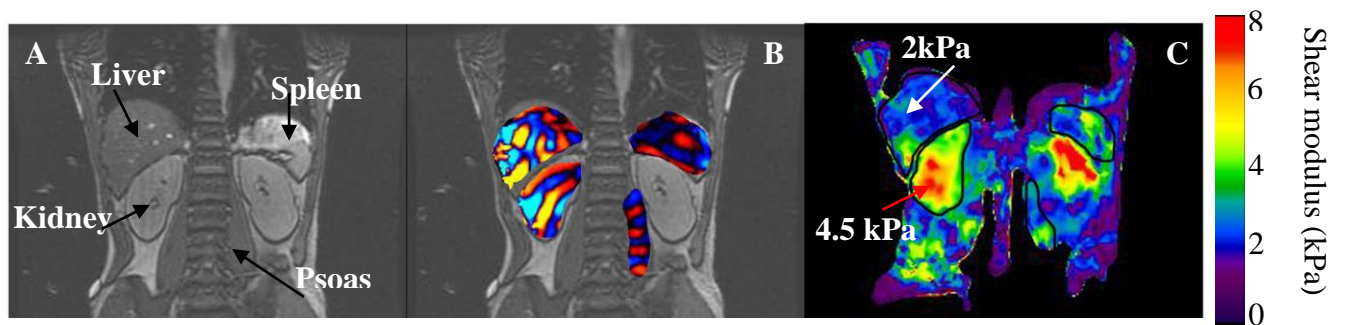


Fig. 2. A: Anatomical image of the liver, the kidneys, the spleen and the psoas trough a coronal oblique plan. B: Phase image showing the propagation of the shear waves inside the four different tissues. C: Cartographies of shear modulus with a region of interest (ROI) placed around each investigated tissues.

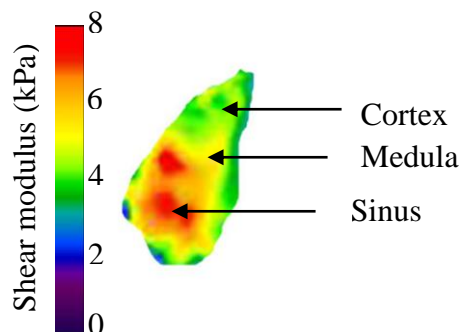


Fig. 3. Spatial distribution of the stiffnesses within the various kidney compartments