

Sodium MRI of the Human Kidney

Y. Rosen¹, N. Maril¹, H. G. Reynolds², A. Ivanishev¹, R. E. Lenkinski¹

¹Radiology, Beth Israel Deaconess Medical Center, Boston, MA, United States, ²GE Healthcare, Milwaukee, WI, United States

Introduction

The major function of the kidney is to maintain body fluids and electrolytes homeostasis by filtering the plasma and excreting end products. This role is largely dependent on the extracellular sodium concentration gradient from the cortex to the medulla (corticomedullary sodium gradient) built up by the counter-current mechanism. This gradient was previously measured in animal kidneys using destructive methods such as micropuncture, radioautographic techniques, and slice section analysis. ²³Na MRI was employed to study the corticomedullary sodium gradient in exposed animal kidneys (1), and recently, non-invasively in the intact rat kidney, characterizing the specific modulations in diuresis, hydronephrosis and acute tubular necrosis (2,3). A number of technical issues can hamper *in vivo* ²³Na imaging, including fast transverse relaxation, low tissue concentration, and the low intrinsic sensitivity of ²³Na compared with protons (¹H). In addition, the multi-medullae structure of the human kidney and its depth from body surface, pose technical challenges involving hardware, pulse sequence design, and image processing. Previous ²³Na MRI studies of the human kidney performed at 1.5 Tesla suffered from either long scanning time or low spatial resolution (4,5). In this study we demonstrate the capability of 3T ²³Na MRI to map the distribution of sodium in the human kidney and to quantify, for the first time, the corticomedullary sodium gradient.

Methods

Volunteers: 6 volunteers (age range 28-37 years) were scanned under normal conditions and after 12h. water deprivation.

MRI: Images were acquired on a 3T scanner (GE, Waukesha, WI). The body coil served for the proton images acquired with 2D T₂-weighted SE, TE/TR=35/4000 ms, FOV=38×38 cm², matrix size=256×256, slice thickness=1 cm. After localizing the exact position of the kidney, the sodium images were acquired with a custom-built quadrature surface coil (Fig.1), using a 3D-GRE sequence, modified for multinuclear imaging, with FOV=38×38×24 cm³, matrix size=128×128×16, TE/TR =1.8/30 ms, 24 averages (25 min). The short echo time was achieved by applying a 66% partial Fourier echo, along with a hard, non-slice selective, 300 μsec RF excitation pulse.

Data Processing: The time domain data was filtered with a 2D Fermi filter before the 3D Fourier transformation, and a heterodyne reconstruction was applied to process the non-symmetric k-space data. Correction for variation in coil sensitivity was performed by reference to a calibration map from a sodium image of a homogenous phantom (60mM NaCl), acquired with the same parameters.

Image Analysis: Analysis of the sodium images was performed in two ways:

1. Regions of interest (ROI's) representing each observed medulla, the cortex, and the noise area were defined and the signal-to-noise ratio (SNR) was measured for each. The sodium gradient was quantified from the ratio of the SNR's of the medulla and the cortex.
2. Pixel-by-pixel analysis along the corticomedullary axis yielded a plot of signal intensity relative to that in the cortex against the distance from the cortex. The corticomedullary sodium gradient was then calculated by fitting the slope to a linear equation.

Results

High signal intensity in the kidney, as well as in the liver and the spinal cord was observed in the sodium images of the human abdomen (Fig.2). Referencing the distribution of the sodium signal intensity to the anatomical structure of the kidney indicated that the signal intensity increased from the cortex to each of the medullae and then decreased toward the renal pelvis, which is consistent with the physiological sodium distribution.

ROI analysis: Average SNR's of 12±2 and 28±2 were measured for the cortex and medulla respectively, resulting in a medulla to cortex ratio of 2.3±0.1 (n=6 kidneys).

Pixel-by-pixel analysis: Sodium signal intensity along the corticomedullary axis yielded consistently a linear increase (R=0.96±0.01), (Fig.3). The mean slope was found to be 0.18±0.01 in relative arbitrary units per mm (Rel.u.×mm⁻¹), (n=6) resulting in an intensity ratio between the tip of the medulla and the cortex edge of 3.78:1.

Water deprivation: The SNR of the medulla was significantly higher (34.8±1.8, n=6, p<0.006) than in the normal conditions, the sodium gradient increased by 13% to 2.6±0.1 (p<0.03). At a pixel resolution, the slope of the relative signal intensity increased by 28% to 0.23±0.01 Rel.u./mm (p<0.003), resulting in an intensity ratio between the tip of the medulla and the cortex edge of 4.75:1 (p<0.006).

3.6±0.5 medullae per kidney were observed in the raw sodium images (n=6), vs. 5.0±0.2 in the MIP (maximum intensity projection) reconstruction of the same images, indicating partial volume effects in the single slice images.

Discussion

In vivo ²³Na images exhibit a SNR that is four orders of magnitude lower than that of *in vivo* ¹H images. Nevertheless, the kidney is clearly observed in sodium images of the abdomen due to its extensive extracellular volume (sodium extracellular concentration is 145 mM), as well as the marked increase in the medullar extracellular sodium concentration produced by the countercurrent mechanism. The ²³Na images, acquired in the coronal plane, clearly show the renal compartments, including the cortex, medulla and renal pelvis, and enable the quantification of the corticomedullary sodium gradient. The pixel-by-pixel analysis depicted this gradient successfully, without applying any averaging process, and therefore it provides a more reliable measurement of the gradient than the ROI analysis. Post imaging analysis may include MIP for observing the medullae, and single slice analysis for sodium gradient quantification. Since relaxation times of sodium were found to be similar in the cortex and the medulla in previous animal studies (1,3), we suggest that the sodium images of the human kidney reflect differences in the concentrations of sodium within the respective tissues. The sodium signal intensity is a volume-weighted mean of the sodium concentrations in their different compartments, namely intracellular, extracellular, and intravascular spaces, as well as intratubular and the vasa recta in the medulla. Therefore, the increase in sodium signal intensity observed in the medulla relative to the cortex may reflect both an actual increase in the concentration in each compartment and an increase in the volume fraction of compartments with higher sodium concentrations. The increased sodium gradient under water deprivation augments water reabsorption from the medullar collecting ducts back to the plasma, enabling the kidney to conserve water and prevent dehydration.

Conclusion

We have demonstrated the use of ²³Na magnetic resonance imaging to detect the spatial distribution of sodium in the human kidney in a non-invasive manner. We have been able to determine the corticomedullary sodium concentration gradient at ~3 mm in-plane resolution, and we showed that this gradient increased significantly under conditions of water deprivation. This work is an important initial step in applying ²³Na MRI of the human kidney at 3T to assess renal function in a variety of physiological and pathological conditions in humans.

References: 1. Wolff SD. et al., *Am J Physiol* 1990;258:F1125-1131. 2. Maril N. et al, *Magn Reson Med*. 2005 Mar;53(3):545-52. 3. Maril N. et al., *Kidney Int*. 2004 Mar; 65(3): 927-35. 4. Ra JB. et al., *J Comput Assist Tomogr*. 1989 Mar-Apr;13(2):302-9. 5. Steidle G. et al, *Magn Reson Imaging*. 2004 Feb;22(2):171-80.



Fig.1. The quadrature surface coil used for sodium imaging. The coil included two loops of 18 cm diameter each that overlapped in 20% of its area in order to avoid coupling between them.

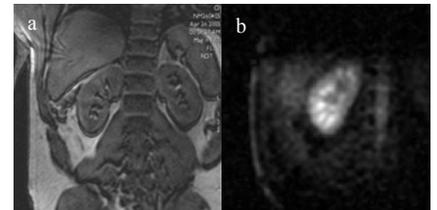


Fig. 2. a) A coronal abdominal proton image. b) The sodium image of the Rt. Kidney under water deprivation. Acquisition parameters of both images are in the text.

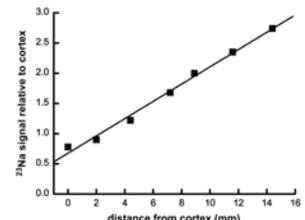


Fig.3. A plot of the sodium signal intensity relative to that in the cortex as a function of the distance from the cortex, showing the linear corticomedullary sodium gradient.