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Magnetic Resonance Imaging 30 (2012) 1192 – 1200

MAGNETIC RESONANCE IMAGING

Comparing anisotropic diffusion filters for the enhancement of sodium magnetic resonance images

Christoph M. Decker, Frank G. Zöllner*, Simon Konstandin, Lothar R. Schad

Computer Assisted Clinical Medicine, Medical Faculty Mannheim, Heidelberg University, 68167 Mannheim, Germany

Received 23 November 2011; revised 7 March 2012; accepted 2 April 2012

Abstract

The anisotropic diffusion (AND) filter, an image processing technique derived from physics, was applied to low-resolution sodium magnetic resonance imaging (MRI) to examine the possibilities of image enhancement by postprocessing. We compared six different variants of AND filters. Besides the qualitative good results on phantom measurements, quantitative analyses on MRI of human kidney yielded major improvements in noise reduction and other quality measures: the noise (i.e., the standard deviation in the image background) could be reduced to 1%–2% of its original value, while linear filters (Gaussian, Fermi, Hamming) achieved a reduction to 42%–64%. Besides that, less than 5% of structures and intensities are lost when using AND filters. Comparing the different variants, the two-dimensional and the three-dimensional AND filter outperformed the histogram-of-gradient and tensor-based AND filter. We envision that by using these AND filters, quantitative analysis of sodium MRI of kidney could be improved.

Keywords: ^{23}Na-MRI; Postprocessing; Anisotropic diffusion filters; Kidney imaging

1. Introduction

Chronic renal failure is an increasing problem worldwide; therefore, developing magnetic resonance imaging (MRI) techniques that can monitor the physiology of the kidney became popular [1–4]. A new emerging technique is sodium imaging of kidney [5–10]. It has great potential, as one of the main purposes of the human kidneys is the maintenance and the regulation of the fluid and electrolyte homeostasis [9]. About 80% of these are sodium (^{23}Na) and potassium, and reabsorption of NaCl dominates most processes of the kidney. It has been shown that the sodium concentration gradient along the corticomedullary axis could be used to measure kidney function [6,9].

In vivo MRI of sodium is limited due to its electrophysiological characteristics. The combination of relatively low in vivo concentration and MR sensitivity of ^{23}Na compared to ^{1}H results in relatively low in vivo MR signal [11,12]. Therefore, it is important for a clinical application to maintain a high signal-to-noise ratio (SNR) and a high resolution at the shortest possible acquisition time. A logical step forward is the enhancement of image intensity by applying postprocessing filters. Thereby, a compromise is reached, allowing for acquiring sodium images at a good resolution in reasonable time. The loss of SNR can be compensated by appropriate postprocessing filtering. Furthermore, Gibbs ringing could be suppressed. Besides linear filters [13,14], other techniques to enhance proton MR images comprising partial differential equations [15], blockwise nonlocal means filter [16] or wavelet-based filtering [17,18] were reported to improve image quality in MRI.

Recently, Fermi filters were applied to sodium MRI to measure the sodium concentration gradient [8]. However, the increase in SNR by linear filters as previously proposed is paid by a loss in resolution, i.e., blurring the images. Especially, in sodium MRI of human kidney, a loss of the contour information is disadvantageous, and measuring the sodium concentration gradient will become difficult. Filters that preserve contours while removing noise are, for example, anisotropic diffusion (AND) filters. These filters model a diffusion process, smoothing areas with weak edges and preserving or enhancing strong edges in the image. The

* Corresponding author. Tel.: +49 (0)621 383 5117; fax: +49 (0)621 383 5123.

E-mail address: frank.zoellner@medma.uni-heidelberg.de (F.G. Zöllner).

0730-725X/$ – see front matter
doi:10.1016/j.mri.2012.04.019

typical blurring of linear filters is reduced. Anisotropic diffusion filtering was first applied to ^{1}H MR images of the brain by Gerig et al. [19]. A noise adaptive AND filter was used on a structural phantom by Samsonov et al. [20]. Initial results on AND filtering in sodium MRI were recently reported [21].

The aim of this study was to compare different anisotropic filters with respect to signal and structure conservation for enhancing sodium MR images of the human kidney.

2. Methods

2.1. Structural resolution phantom

A structural phantom was used to test the feasibility of AND filtering on low-resolution sodium MR images. A blueprint of the phantom is shown in Fig. 1A. The phantom consists of two halves. One half is composed of cylindrical bores and the other half of Plexiglas slabs (not shown). The phantom has a diameter of 20 cm. Bores and slabs are equally arranged. The distance between two bores/slabs is equal to the diameter of the bores. Bore diameters range from 1 to 10 mm. The phantom was filled with saline solution (153 mmol/l) and additional 0.14% $NiSO_4$ to shorten relaxation parameters.

2.2. Image acquisition

All measurements were performed on a 3-T whole-body MR scanner (Magnetom Tim Trio, Siemens Healthcare, Erlangen, Germany). The phantom measurements were performed using a double-resonant (^{23}Na: 32.59 MHz, ^{1}H: 123.2 MHz) birdcage head coil (Rapid Biomedical GmbH, Würzburg, Germany) and a two-dimensional (2D) density-adapted radial sequence [22] with parameters repetition time (TR)/echo time (TE)/flip angle (FA)=50 ms/1.88 ms/66°, readout length per spoke=5 ms, maximum readout gradient amplitude=8.58 mT/m, projections=160, matrix 50×50 and averages=40. The slice thickness was 10 mm, and the nominal in-plane resolution was reconstructed to field of view (FOV)=200×200 mm^2 with pixel size of 4×4 mm^2. Total acquisition time was 5 min and 20 s.

Kidney images were acquired using a density-adapted three-dimensional (3D) radial gradient-echo sequence [11] with parameters TR/TE/FA=120 ms/0.55 ms/85°, nominal isotropic resolution=5 mm, FOV=320×320 mm^2, matrix 64×64×64, readout length per spoke=20 ms, maximum readout gradient amplitude=3.68 mT/m, projections=8000 and averages=1, resulting in a total acquisition time of 16 min. A dedicated, commercially available ^{23}Na-tuned cardiac coil (Rapid Biomedical GmbH, Würzburg, Germany) was utilized for signal reception. It consists of two

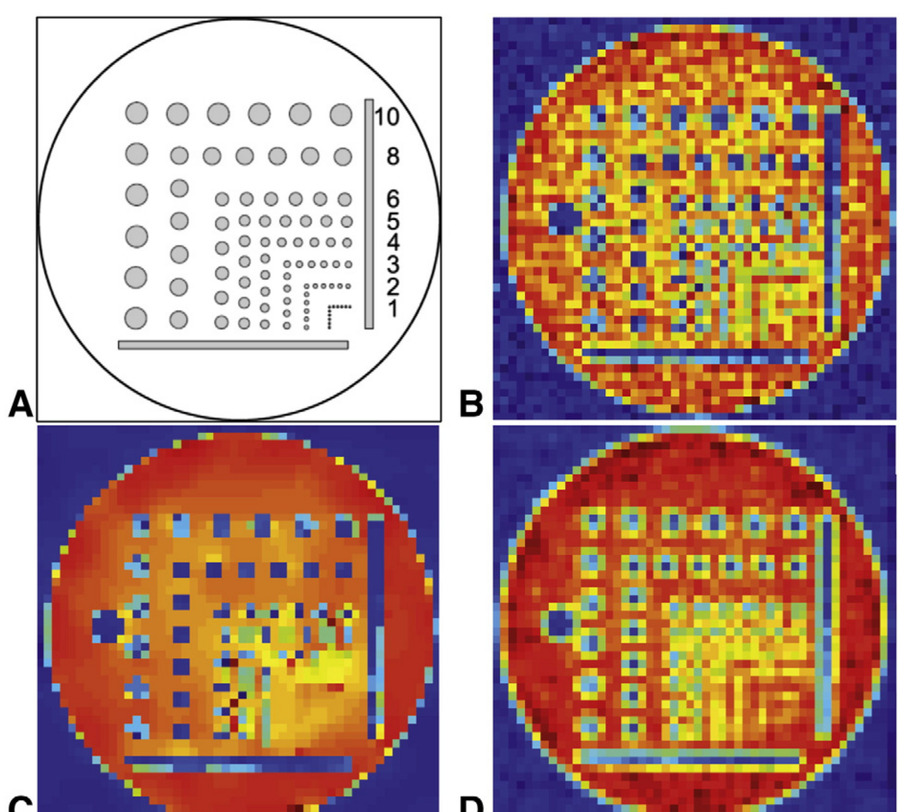

Fig. 1. Sodium MR images of structural resolution phantom (red: high signal, blue: low signal, in-plane resolution: 4×4 mm^2). Blueprint of the phantom (A), original image (B), filtered with 2D-AND (10 iterations, Δt: 0.1, q: 0.6) (C) and filtered with a Hamming window of size 4 (D).