Geometrical Optimization of a Phased Array Coil for High-Resolution MR Imaging of the Carotid Arteries

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The geometry of an RF phased-array receiving coil for high-resolution MRI of the carotid artery, particularly the bifurcation, was optimized with respect to signal-to-noise ratio (SNR). A simulation tool was developed to determine homogeneity, sensitivity, and SNR for a given imaging situation. The algorithm takes into account the coil geometry, the parameters of the measured object, and the imaging parameters of the pulse sequence. The coil with the optimum geometry was implemented as a receive-only coil for 1.5 T and comparative SNR measurements with different coils were performed. The experimental SNR measurements verified the simulations. The optimized carotid artery phased array offered the best SNR over the desired field of view. In vivo high-resolution MRI of the carotid arteries of healthy volunteers and patients with known stenosis was conducted with the optimized phased array coil. The capability of the phased array coil for resolving components within the carotid artery walls is demonstrated. Magn Reson Med 50:439–443, 2003. © 2003 Wiley-Liss, Inc.

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Noninvasive imaging of the carotid arterial wall is of great neurological interest, since carotid atherosclerotic disease is the leading underlying cause of acute stroke. Particularly, the bifurcation is prone to plaque formation due to turbulent blood flow (1). The characterization of this plaque is highly relevant since this determines the probability of rupture (2). With high-resolution MR, the arterial wall can be imaged and information about the structure and composition of plaques can be attained. A resolution of about 100–300 μm in-plane and ±1 mm slice thickness is desirable. This high resolution results in distinguishable voxels with volumes ∆V ≤ 0.1 mm3.

For high-resolution MR, a high signal-to-noise ratio (SNR) per voxel is crucial. At 1.5 T the noise caused by receiving coils with a diameter of about 2–3 cm is of comparable magnitude to the noise of the sample (3).

The carotid arteries are located at a depth of y = −30 to y = −40 mm from the surface. For coordinate definition, see Fig. 1a. To ensure that the bifurcation and adequate sections of the common, internal, and external carotid arteries can be imaged in a clinical situation without need for repeated repositioning of the RF receive coil, an area of approximately ∆x × ∆z = 5 × 8 cm should be covered by the coil. As the carotid arteries are accessible from the side of the neck, a surface coil is well suited for this configuration. The demand for high SNR per voxel, the relatively shallow depth of the carotid arteries, which determines the requisite penetration depth, and the required extended coverage area of the surface coil along the length of the artery make it reasonable to apply phased array surface coils. Surface coil phased arrays for high-resolution imaging of the carotid arteries have been implemented by Hayes et al. (5).

The main goal of the present work, though, was the optimization of the size and placement of phased array elements relative to one another to further enhance the SNR, while maintaining the anatomical coverage (5 × 8 cm) necessary to avoid frequent repositioning of the coil in a clinical situation. This was done by calculating the SNR for different coil geometries. The simulation algorithm was verified by experimental SNR measurements of a homogeneous phantom.

MATERIALS AND METHODS

A simulation tool was developed to determine SNR/∆V for coils with various geometries. The aims of the simulations were: 1) to get an idea of the order of magnitude of the SNR achievable with a certain coil geometry, 2) to compare the coil geometries with one another, and 3) to compare the calculated SNR to the experimentally measured SNR, at least to a constant scaling factor. The simulation takes into account the parameters of the measured object, of the coil, and of the pulse sequence.

Simulated Coils

Various coil geometries were simulated. Five of them are presented here:

- The “Flex Loop Small Coil”, a commercial linearly polarized coil developed by Siemens Medical Solutions (referred to as “Loop S”): two stacked circular turns, 4.6 cm diameter (Fig. 1b).
- The phased array with Hayes’ design (referred to as “Square PA ⊥”): two square elements, each with dimensions ∆x × ∆z = 6.4 × 6.4 cm. With the phased array aligned transverse to the static magnetic field, the overall dimensions of the coil pair were ∆x × ∆z = 10.8 × 6.4 cm (Fig. 1c).
- The phased array with Hayes’ design, but positioned longitudinally with respect to the static magnetic field (referred to as “Square PA ||”): The overall dimensions of the coil pair were ∆x × ∆z = 6.4 × 10.8 cm (Fig. 1d).
- A single rectangular coil (referred to as “Single”) that achieves the anatomical coverage of 5 × 8 cm: dimensions ∆x × ∆z = 5 × 8 cm (Fig. 1e).
- A phased array referred to as “Carotid PA”, consisting...
of two rectangular elements, each with dimensions $\Delta x \times \Delta z = 3 \times 8$ cm, overlapping 1 cm in the $x$-direction. The overall dimensions of the coil pair were $\Delta x \times \Delta z = 5 \times 8$ cm (Fig. 1f). The design of the Carotid PA derived from optimizing the SNR at the depth of $y = -30$ to $y = -40$ mm from the surface over the required coverage area. Based on the fact that for a voxel given at a depth $y$ a variation of the coil dimension yields maximum SNR for a coil radius of $r_C = y/2.23$ for circular coils respective for a width of square coil of $\Delta x = \Delta z = y/1.28$ (15), the optimization was done by consecutive varying the width $\Delta x_1 = \Delta x_2$ of each coil element.

Experimental SNR Measurements

The Carotid PA phased array coil was realized for and all SNR measurements were performed on a Siemens Sonata 1.5 T scanner. The SNR measurements were performed with a 2.0 L volume phantom with three coils that are potentially suitable for high-resolution measurements of the carotid arteries:

- Loop S, a commercial linearly polarized coil available from Siemens Medical Solutions, with dimensions as described above, in combination with the “Flex Interface” of the scanner. The Flex Interface provides pre-
amplification and electrical decoupling of the individual coil elements for phased arrays.

- **Carotid PA**, the self-constructed phased array coil: the Carotid PA was etched on a flexible, double-sided copper laminate (35 μm Cu, 100 μm polyester foil). The elements were geometrically decoupled. During the RF transmission pulses of the body coil, the Carotid PA is actively decoupled. Both single coil elements are tuned (via a parallel capacitance) and matched (via an additional series capacitance) and connected to the Flex Interface for further (electrical) decoupling and preamplification.

- **“CP Neck Array Coil,”** a commercial circularly polarized coil array developed by Siemens (referred to as “CP Neck”) for high-resolution neck imaging. The coil consists of an inflexible linearly polarized element, which is positioned on the mediastinum of the patient, and a pair of flexible CP coil elements, which are fixed at either side of the neck. The size of each neck element is approximately 9 × 14 cm. Only the flexible CP coil elements are used for the experimental SNR measurements.

The phantom was filled with 1.25 g NiSO₄ × 6 H₂O, 5 g NaCl per 1000 g H₂O. The pulse sequence was a 2D spin echo. The fields of view in plane were FOVₓ = FOVᵧ = 80 mm, the acquired and reconstructed matrix size was Nₓ × Nᵧ = 256 × 256, and the slice thickness was Δsₓ = 5 mm. The receiver bandwidth was Δf = 90 Hz/pixel. The number of signal averages was NSA = 1. The pulse repetition time was TR = 300 ms, and the spin echo time was TE = 14 ms. The measured SNRs were compared to the simulated SNR of the Carotid PA, the Loop S, and the Single.

**In Vivo Measurements**

In vivo measurements of five healthy volunteers and eight patients with known carotid artery stenosis were performed with the Carotid PA. Best contrast was achieved with a 2D proton density-weighted fast spin echo sequence. The fixed parameters of the sequence for all measurements were: EKG-triggering with TR = 2 RR intervals (1500–2500 ms), TE = 10 ms, echo train = 7, number of acquisitions = 4, acquired matrix 256 × 256 interpolated to 512 × 512, FOV = 60 × 60 mm, slice thickness = 2–3 mm.

**RESULTS**

Simulations and Experimental SNR Measurements

For easier comparison, the calculated SNR of all five simulated coils is presented in three different ways: Figure 1b–f shows the SNR in the slices y = ±30 mm. Figure 2 shows the SNR profiles in y at x = z = 0 mm (Fig. 2a), and the SNR profiles in z at x = 0 mm, y = ±30 mm (Fig. 2b). Figure 3 shows the measured SNR profiles in y at x = z = 0 mm, y = ±30 mm.
0 mm (Fig. 3a) and the measured SNR profiles in $z$ at $x = 0$ mm, $y = −30$ mm (Fig. 3b). For a summary of the results of the simulations and experimental SNR measurements, see Table 1.

In Vivo Measurements

A 2D thick slice phase contrast MR angiogram (PC MRA) that served as localizer for imaging the right carotid artery of a healthy volunteer (Fig. 4a) indicates the sensitive area of the Carotid PA of more than 80 mm in the $z$-direction. The horizontal white line indicates the position of the axial slice presented in Fig. 4b. For Fig. 4b the parameters of the pulse sequence for the axial slice were $TR = 2458$ ms, slice thickness 2.9 mm, $FOV_x = FOV_y = 60$ mm. For $TE$, echo train, number of acquisitions, and matrix, refer to Materials and Methods. The carotid artery of this volunteer is situated at a depth of 20–30 mm from the surface.

Figure 5 shows the sagittal (Fig. 5a) and axial (Fig. 5b) slices of a patient with stenosis of the left common carotid artery. The white line in Fig. 5a indicates the position of the axial slice, the white line in Fig. 5b indicates the position of the sagittal slice. The parameters of the pulse sequence were $TR = 1810$ ms, slice thickness 2.0 mm, $FOV_x = FOV_y = 80$ mm for Fig. 5a, and $TR = 1915$ ms, slice thickness 1.5 mm, $FOV_x = FOV_y = 84$ mm for Fig. 5b. The carotid artery of this patient is situated at a depth of 25–35 mm from the surface.

**DISCUSSION**

Simulations and SNR Measurements

The strong agreement between theoretical predictions and experimental results is obtained because the two main reasons for false estimation are eliminated. One factor is the unknown noise resistance of the electronics of the coil $R_E$. For the calculations, the $R_E$ measured for actual constructed coils is taken as a priori information. The other factor is the volume for which the electromagnetic fields are calculated. The simulations are performed for a semi-infinite half space. In the experiments, the sample was a 2 L cylinder which was large enough such that the electromagnetic fields are decreased to negligible levels at the boundaries of the sample. For smaller samples there would be a large difference between numerical calculation and experimental results. Thus, the implemented simulation algorithm proved to be an accurate and valuable tool for predicting the expected SNR for a given coil geometry arrangement.

Comparison of the simulations of the Single and the Carotid PA shows the superiority of a phased array design consisting of two smaller elements, with the same final overall coil dimensions. Even at depths greater than the maximum overall coil dimension, the phased array offers a higher SNR. The top performance position of the Carotid PA in the simulations as well as in the experimental measurements makes it the most favorable design for imaging the carotid arteries. For adipose patients, the carotid arteries may be situated even deeper than assumed in the

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<td>Good agreement of simulation and experiment, sufficient at $y = −30...−40$ mm, sufficient anatomical coverage in $x$, $z$-direction</td>
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**FIG. 4. Images of a healthy volunteer:** (a) localizer (white line = position of the axial slice), (b) axial slice of the right common carotid artery.
simulations \((y = -40 \text{ mm})\). However, even at depths between \(y = -40 \text{ mm}\) and \(y = -70 \text{ mm}\), the Carotid PA is predicted to achieve the highest SNR.

In Vivo Measurements

The in vivo measurements obtained with the Carotid PA are of excellent quality. The high SNR at the depth of the carotid arteries along a span of more than 80 mm in the \(z\)-direction allows imaging the bifurcation and inferior and superior carotid segments without repositioning of the coil. The arterial wall could clearly be distinguished, even in healthy volunteers where the wall is very thin. In patients with advanced atherosclerotic changes, the plaque and various structures within the plaque could be resolved and distinguished. Thus, this phased array design appears to be suitable for MRI of carotid plaques.

In clinical practice, bilateral imaging of the carotids is often desirable for a direct comparison of both carotid arteries. Bilateral imaging would in principle be possible with a pair of Carotid PA, as there is no coil–coil interaction observable. This is an advantage of the negligible sensitivity of the Carotid PA at depths deeper than \(y = -70 \text{ mm}\). However, bilateral imaging would require a field of view expansion of about a factor of three in the \(x\)–(sagittal)-direction. To achieve the same high in-plane resolution of 312 \(\mu\text{m}\) measured (156 \(\mu\text{m}\) interpolated), the acquisition time would expand by a factor of three as well. If the number of pixels in the \(x\) (sagittal)-direction were held constant, the voxel size would be so large (and resolution would be so poor) that the SNR of the commercial CP Neck coil would be sufficient. Thus, we prefer to perform the left and right measurements independently, giving only a factor two increase in time.

The ability to determine the structure of carotid plaques is of great interest, since it might provide some predictive value of which plaques are most likely to rupture and lead to embolus. In addition, the ability to reliably and repeatedly monitor the size and make-up of a given plaque would be a useful tool for monitoring the success of various treatment regimens designed for reducing plaque size, for instance, new genetic therapies.

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REFERENCES