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Rapid Development of Application-specific Flexible MRI Receive Coils

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Abstract

Over the last 30 years, there have been dramatic changes in phased array coil technology leading to increasing channel density and parallel imaging functionality. Current receiver array coils are rigid and often mismatched to patient's size. Recently there has been a move towards flexible coil technology, which is more conformal to the human anatomy. Despite the advances of so-called flexible surface coil arrays, these coils are still relatively rigid and limited in terms of design conformability, compromising signal-to-noise (SNR) for flexibility, and are not designed for optimum parallel imaging performance. The purpose of this study is to report on the development and characterization of a 15-channel flexible foot and ankle coil, rapidly designed and constructed using highly decoupled RF coil elements. Coil performance was evaluated by performing SNR ratio and g-factor measurements. In vivo testing was performed in a healthy volunteer using both the 15-channel coil and a commercially available 8-channel foot coil. The highly decoupled elements used in this design allow for extremely rapid development and prototyping of application-specific coils for different patient sizes (adult vs child) with minimal additional design consideration in terms of coil overlap and geometry. Image quality was comparable to a commercially available RF coil.

Keywords

flexible RF coil; rapid development; anatomy-specific coils; foot and ankle coil; radio-frequency (RF) coils; magnetic resonance imaging (MRI)

1. Introduction

Over the last decade, there has been a significant effort to enable ultra-flexible coil technology that is more conformal to the human anatomy and, in turn, improves magnetic resonance imaging (MRI) through signal reception and patient comfort. Application-specific flexible and conformal coils for a variety of body regions have been prototyped (Vasanawala et al. 2017, McGee et al. 2018, Zhang et al. 2018, Behzadnezhad et al. 2018, Behzadnezhad et al. 2019, Corea et al. 2016). There have also been concurrent and dramatic changes in phased array technology in terms of increasing element density largely driven by the development of parallel imaging methods (Ohliger & Sodickson 2006, Asher et al. 2010, Zhu et al. 2004, Shapiro et al. 2012). Increasing the number of elements requires considerable design effort to determine the size, placement, and amount of overlap of the individual coils (Fujita 2007, Roemer et al. 1990).

In 2017, a new highly flexible and light-weight RF coil element was introduced and characterized referred to as adaptive image receive (AIR) coil (Vasanawala et al. 2017). These coils have unique electrical properties which significantly minimizes the effect of mutual inductance and coupling between coils. This allows for both an increase in the number of channels and utilization of geometric coil configurations that could not be easily achieved using conventional RF surface coils. Since overlap and coil shape are no longer strict constraints, it is straight-forward to rapidly develop application-specific coils that match patient's anatomy by simply increasing/decreasing the number of elements and their placement.

For the purpose of this study, we focused on the development of a flexible and conformal foot and ankle coil using the AIR technology. Current receive-only RF coils for this anatomical application are constrained in terms of rigidity and design. The inclusion of necessary RF circuit components (blocking, tuning, etc.) close to each element further adds to their rigidity and physical weight. Note that flexible coil design has been previously demonstrated for musculoskeletal (MSK) imaging (Nordmeyer-Massner et al. 2012, Jia et al. 2015, Frass-Kriegl et al. 2018). However, these coils are still relatively limited in terms of design flexibility and conformability despite the development of so-called flexible surface coil arrays. Also, magnetic field homogeneity and SNR can vary significantly under different placements (Gao et al. 2016).

In this note, we designed and built a 15-channel flexible coil used for foot-ankle imaging using AIR coil elements for 3T MRI. A key aspect is the rapid development of the coil enabled by the minimal mutual coupling of the AIR coil elements. We demonstrate that by using AIR elements, novel and application-specific configurations and geometries can be developed rapidly with minimal design effort in terms of coil positioning and overlap, while delivering comparable performance compared to a currently available commercial coil. Phantom studies were performed to compare the performance of the coil to a conventional rigid foot coil. SNR maps and noise correlation matrices were calculated for both coils. Parallel imaging performance was assessed by calculating g-factor maps. In vivo testing was performed using both coils on a healthy volunteer.

2. Methods

2.1. RF coil description

The AIR coil elements were provided by GE Healthcare (Waukesha, WI). The elements are 11 cm in diameter and fabricated using a flexible conductor (approximately 0.6 mm thick (Fig. 1(a))). The coils have no physical lumped components and are therefore highly flexible and able to conform to various human anatomy. Each element is attached to a feed-board of dimensions 22×22×10 mm. The integrated feed board contains the matching and decoupling circuit, preamplifier, and a balun. We created a 15-channel foot-ankle coil using AIR coil elements using 15 coil elements in two rows of 8 and 7 coils to create an array of dimensions 65 × 20 cm that enables full coverage of the foot and ankle (Fig. 1(b)). The coils were attached to a 1/16" plastic sheet. Coil overlaps were chosen to be approximately 10 mm in both planar dimensions, as previous studies demonstrate that this spacing provides the lowest g-factor (McGee et al. 2018). Note that due to flexibility of the individual AIR coil elements and a manual construction method, inter-array spacing was approximate, and was not exact. Due to the minimal mutual inductance of the AIR coil elements, no additional design considerations in array placement and no retuning of the individual elements was necessary. The time required to assemble the complete array and cabling was less than 6 hours.

2.2. Signal-to-noise ratio

All imaging tests were done on a 3T GE-Healthcare Signa scanner. The SNR of the two coils were compared by collecting axial and sagittal images. SNR was calculated using Method 2 described in NEMA Standards Publication MS 1-2008 (R2014). We used the test phantom provided by Invivo Corporation (Orlando, FL), as seen in Fig. 2(a), and their 8-channel Foot and Ankle coil (a commercial coil specifically designed and recommend for foot and ankle imaging), as seen in Fig. 2(b) and referred herein as the *commercial coil*. The commercial coil has no receive element at the base of the heel or along the leg. In contrast, the AIR coil elements wrap around the base providing full coverage. For SNR comparison, a spin-echo scan was performed with the following parameters: echo time (TE) = 20 msec, repetition time (TR) = 750 msec, field of view (FOV) = 28×28 cm, slice thickness = 3 mm, matrix size = 256 × 256. SNR maps were computed using the image difference method and compared across both coils (Price et al. 1990).

2.3. Noise correlation matrices analysis

Noise correlation matrices were calculated for both 8-channel commercial coil and 15-channel foot-ankle AIR coil to estimate the amount of correlated noise between various coil elements in each coil array. We used the same test phantom for both coils.

2.4. Assessment of parallel imaging performance

G-factor maps were calculated for both the 8-channel commercial coil and the 15-channel AIR Coil arrays (Montin et al. 2019). Fully sampled k-space data were collected for both coils. The same raw data used for SNR characterization was used for g-factor assessment. A sensitivity map of each coil was produced by dividing the reconstructed image of a coils by

the combined image generated from all the coils. The same data was used to produce under sampled data sets for SENSE processing with acceleration values of 2, 3, and 4 (Pruessmann et al. 1999). G-factor maps were produced for both axial and sagittal scans. The phase encoding direction was set to A/P.

2.5. In vivo testing

High resolution fast spin echo with short tau inversion recovery fat suppression (FSE-STIR) images were taken to evaluate the in vivo performance. The scan parameters were: echo train=12, TE=43 msec, TI=170 msec, TR=13205 msec, FOV=28×28 cm, thickness=2 mm, matrix size=384 × 384, bandwidth=20.8 kHz. For these scans the parallel imaging acceleration factor was 2 using Autocalibrating Reconstruction for Cartesian Imaging (ARC) (GE Healthcare, Waukesha, WI). Fig. 2(b–d) shows the placement of both coils on the volunteer's foot. All scanning was performed under local ethics committee approval. The AIR Coil was covered in Nomex flame rated material (Dupont de Nemours, Inc.; Wilmington, DE) prior to scanning for safety.

3. Results

3.1. Phantom testing

Fig. 3 shows the SNR maps for the two coils. The signal was determined by taking the signal average of the two sequential images. Noise was determined by subtracting the two images from each other. SNR was calculated for two regions of interest (ROIs) at the center of the axial image (ROI 1) and the ankle and leg part of sagittal image (ROI 2). For ROI 1, the SNR was 1886 for the 8-channel coil and 1666 for the flexible 15-channel coil. However, at the base of the coil (ankle) where the 15-channel coil has coverage, the SNR was 1453 vs 8-channel coil which was 1295.

The noise correlation matrices for the 8-channel commercial coil and the 15-channel AIR coil are shown in Fig. 4. The off-diagonal elements describe noise correlations between multiple element. The diagonal elements of the matrix describe noise power of a given element. Values are normalized to 1.0. Note that the small increase in noise correlation in 15-channel coil is expected because it has higher number of smaller elements compared to the 8-channel coil. Additionally, the geometry of the 15-channel coil was not optimized for conformal use (elements were placed with fixed spacing in a 2D grid). Imaging results for the two coils show that the 15-channel coil has comparable SNR performance but performed significantly better in parallel imaging. Maps of $g\sqrt{R}$ for both coils in axial and sagittal slices are seen in Fig. 5. Both coils performed well for $R = 2$ with the 8-channel coil performing slightly better. The 15-channel AIR Coil performed well with g-factors near 1 for all measured acceleration values.

3.2. In vivo testing

Fig. 6 shows sagittal images of the foot and ankle obtained from a healthy volunteer using both the 8-channel commercial coil (Fig. 6(a)) and the 15-channel AIR coils (Fig. 6(b)) and. These images were not filtered so regional differences in SNR could be more easily observed. Fig. 6 also illustrates the regional differences in SNR with the commercial coil toe

region exhibiting higher SNR while the AIR Coil has higher SNR in the ankle and leg region. The images show that both coils have similar image quality. The slight differences in slice location are due to repositioning of the subject when exchanging coils.

4. Discussion

This work describes development and characterization of an application-specific flexible coil array rapidly developed and used for imaging the foot and ankle. The unique properties of AIR coil elements, flexibility and significantly reduced mutual inductance and capacitive coupling between the elements allow the coils to conform to the human anatomy without compromising SNR. AIR elements allow building and prototyping application-specific coils with higher coil density configurations in much shorter time (potentially in less than one day, as demonstrated herein) compared to conventional RF coil design techniques where considerable effort should be dedicated to the size and placement of individual coils and the amount of overlap between adjacent coils to overcome decoupling issues. The minimized requirements of AIR coils create the opportunity to increase or decrease coil array density and build application/anatomy-specific conformal coils for complex patient surfaces and different patient anatomies and sizes.

The coil array in this study uses 15 AIR coil elements with 11 cm diameter. The AIR element loop size dictates the number of the elements required to cover the anatomy, thus a higher number of coil elements were needed compared to the commercial coil. Coil elements were placed with a fixed 10 mm of overlap in a 2D planar configuration. No additional design considerations were required to manage mutual inductance between individual elements. In addition to these advantages, the 15-channel AIR coil design allowed improved parallel imaging capabilities compared to an 8-channel commercial foot and ankle coil, with potentially enabling acceleration rates of up to $R=4$. Because the rigid 8-channel commercial coil uses larger elements to achieve coverage and uniformity, it is not optimized for parallel imaging performance.

The main benefit of using flexible RF coils compared to rigid coils is achieving higher SNR in case of strong variations of the targeted anatomy across patients. Developing flexible RF coil arrays comes with several challenges. First, the material used for constructing the flexible RF coil could compromise SNR. For example, flexible substrates used in previously published flexible MSK coils have lower quality factor and higher losses due to the use of thin conductors (Frass-Kriegl et al. 2018). In addition, instability of coil electronics, due to tuning and matching components, solder joint connections, makes previously proposed flexible MSK coil's performance position dependent. The coil array used in this paper uses elements that provide both flexibility and robustness in terms of coil performance with any arbitrary geometrical positioning. The most common strategy in coil array design is to overlap adjacent loops. This increases the complexity in design of dense coil arrays and restricts coil geometry. Additionally, most decoupling methods cannot simultaneously decouple adjacent and non-adjacent elements. The AIR elements used in this paper are significantly decoupled from each other as shown previously (Vasanawala et al. 2017). These highly decoupled elements enable rapid coil array development and prototyping as

individual coil elements can be placed next to adjacent coils in ways that optimize imaging performance (e.g., SNR, g-factor) rather than minimizing mutual inductance.

This work provides both quantitative and qualitative data illustrating the performance characteristic of a rapidly-prototyped 15-channel foot-ankle AIR coil compared to a conventional rigid copper-based design 8-channel commercial foot coil. SNR maps for both coils were illustrated. While there are subtle regional differences in SNR, both coils provided the SNR necessary to image the smaller structures of the foot and ankle. Notably, the 15-channel AIR coil performed significantly better in parallel imaging. The g-factor maps (Fig. 4) show similar performance at g-factors of 2, with the AIR coil performing significantly better at acceleration values of 3 and 4. This performance was expected due to the increased number of elements in the AIR coil array. In vivo testing data from a healthy volunteer demonstrated that the 15-channel AIR coil can conform closely to an individual's anatomy and provide comparable images to the commercially available RF coil. With the availability of highly decoupled RF coil elements, future developments in MR imaging can be made more personalized with anatomically-optimized coils to improve comfort and image quality for all patients.

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Figure 1:
(a) Single AIR coil element with encased feed board, (b) flexible 15-channel foot coil with AIR elements. Elements are labeled 1–15.

(a)

(b)

(c)

(d)

Figure 2:

(a) Phantom used for performance characterization. (b) 8-channel commercial coil placement on volunteer's foot. (c and d) Placement of 15-channel AIR coil array on volunteer's foot.

15-channel coil with AIR elements

Figure 3:
Axial and sagittal SNR maps comparing the 15-channel AIR coil and the 8-channel coil. (a) and (c) show the foot part and (b) and (d) show the foot and leg part of the phantom.

Figure 4:

Noise correlation matrices for 15-channel AIR coil and 8-channel commercial coil. Noise correlation of the AIR coil was evaluated wrapped around the phantom. Coil element number 1 is top left.

Figure 5:

Showing $g\sqrt{R}$ for the axial and sagittal slices. Frequency direction is RL for axial and SI for sagittal slice.

Figure 6:

Sagittal images of a healthy volunteer using (a) 8-channel commercial clinical ankle coil array and (b) 15-channel AIR coil array. White arrows highlight areas of higher SNR in the toe region for commercial coil and in the ankle, heel and lower leg for AIR coil.