Magnetic Resonance Imaging 53 (2018) 164–172

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

journal homepage: www.elsevier.com/locate/mri

Original contribution

Evaluation of stacked resonators to enhance the performance of a surface receive-only array for prostate MRI at 3 Tesla

Jorge Chacon-Caldera[a,*], Alexander Fischer[a], Matthias Malzacher[a], Yannik Vetter[a], Mathias Davids[a], Martina Flöser[b], Christopher Stumpf[c], Lothar R. Schad[a]

[a] Computer Assisted Clinical Medicine, Medical Faculty Mannheim, Heidelberg University, Mannheim, Germany
[b] Medical Physics in Radiology, German Cancer Research Center (DKFZ), Heidelberg, Germany
[c] Work Microwave, Holzkirchen, Germany

ARTICLE INFO

Keywords:
RF receive coils
Coil arrays
Stacked resonators
Prostate MRI

ABSTRACT

Prostate MRI is an important tool to diagnose and characterize cancer. High local sensitivity and good parallel imaging performance are of paramount importance for diagnostic quality and efficiency. The purpose of this work was to evaluate stacked resonators as part of a surface receiver array for prostate MRI at 3 Tesla. A base array of 6-channels consisting of a flexible anterior and a rigid posterior part were built each with three loop coils. A pair of stacked resonators was added concentrically to the center loops (anterior and posterior) of the base array. The evaluated stacked resonators were butterflies, composites and dipoles which yielded a total of three 8-channel arrays. The arrays were compared using noise correlations and single-channel signal-to-noise ratio maps in a phantom. Combined signal-to-noise ratio maps and parallel imaging performances were measured and compared *in vivo* in 6 healthy volunteers. The results were compared to the base and a commercial array. The SNR values in the prostate yielded by all the arrays were not statistically different using fully sampled k-space. However, significant differences were found in the parallel imaging performance of the arrays. More specifically, up to 88% geometric factor reduction was found compared to the commercial array and up to 83% reduction compared to the base array using butterfly coils. Thus, signal-to-noise ratio improvements were observed with stacked resonators when using parallel imaging. The use of stacked elements, in particular butterfly coils, can improve the performance of a base array consisting solely of single loops when using parallel imaging. We expect prostate MRI at 3 Tesla to benefit from using combinations of single loops and stacked resonators.

1. Introduction

The high incidence of prostate cancer requires robust and reliable methods to diagnose and characterize the disease. MRI has long been recognized as an important diagnostic tool for this purpose. Furthermore, it has recently been demonstrated that MRI can also be used to rule out cases where prostate cancer is falsely suspected, thus avoiding the need for biopsies [1]. The main pre-requisite for prostate MRI is: high local sensitivity in the prostate with efficient acquisition times to image the larger abdominal cavity. In terms of sensitivity, the location of the prostate complicates the signal detection due to the coil sensitivity drop as the distance from the coil increases. When using surface coils, this distance is determined by the anatomical location of the prostate with respect to the surface of the body. An approach to overcome this limitation is the use of tailored endorectal coils which can be placed near the prostate using the rectal cavity [2]. However, there exists controversy in the literature regarding the advantages of using this type of coils [3–7]. Moreover, they are uncomfortable for patients. For these reasons, arrays of surface coils are often preferred despite an arguable reduction in signal-to-noise ratio (SNR) in the prostate. The limit in SNR has an impact on image quality and it could compromise the diagnostic quality of the images. Therefore, it is important to maximize sensitivity of the surface arrays. Likewise, achieving efficient scanning times, is of high clinical relevance. For this

Abbreviations: SNR, Signal-to-noise ratio; G-factor, Geometric factor; REF, Reference/base; COM, Commercial; B3SL, Base array with a pair of butterfly coils; C3SL, Base array with a pair of composite coils; D3SL, Base array with a pair of dipole antennas; AP, Anterior-Posterior; LR, Left-Right; SD, Standard deviation; SENSE, Sensitivity encoding; FOV, Field-of-view; ROI, Region-of-interest; A, Anterior; P, Posterior; L, Left; R, Right; S, Stacked; C, Center; Dir, Direction; Acc, Acceleration

* Corresponding author at: Computer Assisted Clinical Medicine, Medical Faculty Mannheim, Heidelberg University, Theodor-Kutzer-Ufer 1-3, 68167 Mannheim, Germany.

E-mail address: jorge.chacon@medma.uni-heidelberg.de (J. Chacon-Caldera).

https://doi.org/10.1016/j.mri.2018.07.010
Received 26 March 2018; Received in revised form 8 June 2018; Accepted 21 July 2018
0730-725X/

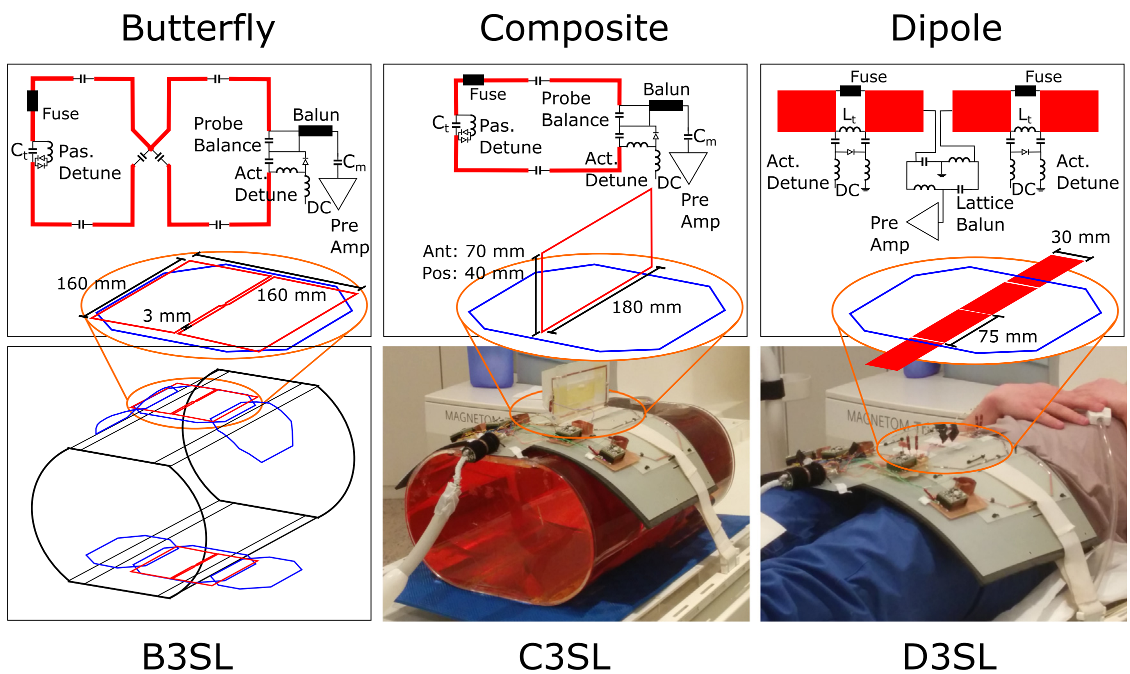

Fig. 1. Schematic design of the tested stacked resonators and their reception chain. Their position and dimensions compared to the center loop is shown (Top). The stacked arrays are shown in a representative design and representative setups for phantom, and *in vivo* measurements (Bottom).

purpose, parallel imaging techniques are the most common approach used in clinical. However, parallel imaging techniques yield an intrinsic SNR penalty determined by the receiver array. This penalty is characterized in terms of the geometric factor (g-factor) and must also be considered in the design and evaluation of RF coil arrays [8].

Standard approaches to the design of RF coil arrays rely on loop coils decoupled by overlap [9–12]. The design in that case can be focused on placing the maximum number of single loop coils that fit an area determined by the application [13–15]. This is feasible due to the large number of available reception channels in modern MRI systems. For body imaging, arrays of up to 128 single loop coils have been built with limited SNR increase in the center of the body but improved parallel imaging performance [16]. However, this approach entails several technical limitations such as a reduction in individual performance of the coils due to coupling with next nearest neighboring coils, higher contribution to noise from coil resistance and reduced penetration depth.

Several works have outlined that the maximum sensitivity in the center of the body (calculated as a homogeneous cylinder) can be well approximated with a limited number of single loop coils following the calculations of ultimate intrinsic SNR [17, 18]. Nevertheless, it has been proposed that additional resonators could complement the $\mathbf{B}_1$-field components of the single loop coils and contribute further towards the sensitivity of RF arrays. Therefore, a combination of these resonators with single loops could yield SNR values closer to the ultimate intrinsic SNR. The impact has been investigated theoretically by several authors in simulations and experimental setups [19, 20]. Three main types of resonators have been investigated: butterfly and composite coils as well as dipole antennas. In this work we refer to these resonators as *stacked elements* to simplify the coil/antenna terminology. These stacked elements also allow geometrical decoupling when placed concentrically with loop coils. This represents an advantage over single loop coils which can only be decoupled geometrically using controlled lateral placement. Butterfly coils have been traditionally used in combination with single loops in MRI for quadrature detection [21–26]. Composite coils are single loop coils placed orthogonally with respect to the standard single loop coils and they have been seldom investigated [27, 28]. Another recently introduced approach is the use of dipole antennas [29]. This approach has been more explored as a standalone element [30] and in combination with single loop coils [31, 32]. Gains have been demonstrated in arrays using both novel approaches combined with single loop coils *e.g.* composite coils in simulations and measurements of a cuboid phantom [28] and dipole antennas in body imaging at 7 T [32]. Moreover, using simulations the dipole has shown to have a similar performance as the single loop in the target depth of the prostate at a range of magnetic field strengths [30].

The aim of this work is to experimentally investigate three different stacked elements in a simple setup with low element count. This was designed to facilitate the characterization of the elements and to test their performance as part of a base array composed of single loop coils. Moreover, a comparison to a commercial solution is provided to ultimately obtain gains in SNR when using parallel imaging in prostate MRI at 3 T.

2. Materials and methods

All methods were performed according to the relevant guidelines and regulations. The *in vivo* prostate scans were approved by the local Institutional Review Board and acquired with prior written informed consent.

2.1.1. Arrays design

An array composed of a flexible anterior and a rigid posterior part was used for the base of our analysis and also for reference (REF array). Each part of the REF array was composed of three single loops decoupled by overlap. The dimensions of the three loops were $180 \times 180\,\text{mm}^2$ for the center loop and $120 \times 180\,\text{mm}^2$ for the side loops. This resulted in a total dimension of $360 \times 180\,\text{mm}^2$ for each part of the array. The dimensions of the center loop were experimentally optimized for the depth of the prostate. The side loops were reduced in size (x-axis) compared to the center loop to minimize coupling between anterior and posterior parts of the array. The dimensions were also chosen to achieve full loading of the loops to maintain sample dominated noise. Stacked elements were added at the center of the two