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Design and testing of a 1.5 Tesla double-tuned ($^1H/^{31}P$) RF surface coil with intrinsic geometric isolation

Maria Alfonsetti, Antonello Sotgiu, Marcello Alecci *

Dipartimento di Scienze della Salute, Università dell'Aquila, 67100 L'Aquila, Italy

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ABSTRACT

We analyse the isolation characteristics of axial and transverse field surface radio frequency coils, used to design a double-tuned surface coil composed by two coils, that combine proton (^1H) detection and localized spectra of phosphorous (^{31}P). Several geometrical configurations were analysed, including circular loop and figure-of-eight coils, with the aim to optimize the isolation between the two channels. Our analysis shows that by using at least one transverse coil for the design of the double-tuned probe, it is possible to achieve a good intrinsic geometrical decoupling, without the need of additional decoupling circuits. On the basis of the experimental results, we have designed and built a 1.5 T double-tuned probe composed by a circular loop coil and a transverse field coil, with the external coil tuned at the ^1H frequency and the internal coil tuned at the ^{31}P frequency, that shows a good intrinsic decoupling and signal-to-noise ratio.

1. Introduction

Over a number of years, an area of increasing interest in the use of *in vivo* magnetic resonance (MR) techniques has been MR spectroscopy (MRS) for preclinical [1] and clinical [2] applications. These studies aim at the *in vivo* detection and quantification of the MR signal of water protons (^1H) and also other low-gamma nuclei of biological interest, like ^{13}C, ^{19}F, ^{17}O, ^{23}Na, ^{31}P, and others [3–8].

Most of the MRS instrumentation is equipped with specially designed double-tuned radio frequency (RF) coils necessary for the generation of the transmitting RF pulses and the detection of the MR signals of the nuclei under investigation. Generally, the ^1H channel is used for anatomic localization and main magnetic field shimming, and the X-nuclei channel for the acquisition of spectra from a well defined region-of-interest (ROI). The double-tuned RF surface coil can be designed either with a single coil pattern, tuned to both frequencies, or with two separate coils, each one tuned at the corresponding low (e.g. ^{31}P) and high (^1H) frequencies. Each one of these designs has advantages and disadvantages and a number of previous workers have investigated these aspects [9–18].

For the geometry employing two separate coils, a critical design goal is the decoupling (isolation) of the two resonant circuits [19]. In fact, if the RF coils are not well isolated the mutual inductive coupling gives a splitting and/or displacing of the resonant frequencies with a consequent signal-to-noise ratio (SNR) losses and image artefacts. A number of design strategies have been proposed for optimising the decoupling of double-tuned RF probes made by two separate RF coils.

A first design comprises two standard square (or circular) loop coils for ^1H and X-nuclei resonance frequencies. A trap circuit (LC resonant circuit tuned at the ^1H frequency placed in series with the X-nuclei loop) allows a good decoupling [18]. Nevertheless, this design shows the disadvantage of some degree of power losses in the trap circuit, with a consequent sensitivity decrease in the X-nuclei channel.

A different strategy proposed originally for ^1H and ^{31}P MRS [20–23], involves a probe made with a standard

* Corresponding author. Address: Dipartimento di Scienze della Salute, Università dell'Aquila, Via Vetoio, 67100 L'Aquila, Italy. Tel.: +39 0862 433639; fax: +39 0862 433785.
E-mail address: marcello.alecci@univaq.it (M. Alecci).

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single-loop RF coil for ^{31}P MRS and a transverse field *butterfly* RF coil (made by two linear elements intersecting at some angle in the central ROI and connected by two return current paths) for ^{1}H decoupling. This design comprises two intrinsically decoupled coils, made by an axial field coil, that generate a B_1 field directed along the coil axis, and a transverse field RF coil, that generate a B_1 field directed along the coil plane. Because of their field configuration, the inductive coupling between the coils is minimized when they are positioned in the same plane. This double-tuned RF coil configuration, presenting intrinsic geometrical isolation, is of interest for MRS applications because it does not require additional trap circuits or active/passive decoupling circuits.

Another RF surface coil design that presents the same characteristics of intrinsic decoupling is the transverse field RF surface coil called *figure-of-eight* (FO8) RF coil (made by two linear elements parallel to each other and connected by two return current paths). Recently, it was shown that the FO8 coil presents an improved sensitivity and selectivity with respect to the CL coils, and shows a high versatility for use in several clinical applications [24–26]. Despite earlier work, reporting quadrature designs with the use of transverse field FO8 coils [27–30], to the best of our knowledge, a detailed comparison between geometrical decoupling techniques employing transverse field FO8 RF coils has not been previously reported.

In this work we have analysed and compared the isolation characteristics of three different sets of RF coils, each set composed by circular coils arranged as: two loop coils, one loop coil and one FO8 coil, and two FO8 coils. For each configuration we have measured the isolation between the transmitter (TX) and receiver (RX) as a function of the coils geometry and relative mutual position. Our analysis shows that by using at least one transverse field FO8 coil for the design of the double-tuned probe, it is possible to achieve a good intrinsic decoupling, without the need for trap circuits and/or decoupling circuits (active or passive). To prove the concept, we have designed and built a double-tuned RF probe suitable for MRI/MRS at 1.5 T. The prototype is composed of a loop coil (diameter 14 cm) and a FO8 coil (diameter 10 cm), with the external coil tuned at the ^{1}H frequency and the internal coil tuned at the ^{31}P frequency. Data acquired with a 1.5 T MR scanner shows a good intrinsic decoupling and SNR without the need of trap circuits. This simple design makes the development and use of double-tuned RF coils at 1.5 T straightforward and very inexpensive.

2. Materials and methods

In this study we have selected two basic coil geometries: the standard circular loop (CL) coil and the figure-of-eight (FO8) coil. The CL coil produces in the central region-of-interest (ROI) an RF B_1 field directed perpendicularly to the coil plane (*axial field RF surface coils*) [31]. The maximum amplitude of the B_1 field is found at the center of the coil plane and it decreases as the distance from the coil axis increases. Recently, a detailed analysis of multi-turn spiral surface coils for MRI microscopy and spectroscopy was reported [32].

The FO8 coil produces in the central ROI a transverse RF B_1 field, since the currents flowing in the linear elements produce a B_1 field that is, substantially, parallel to the coil plane (*transverse field RF surface coils*). In previous studies, it was shown that for particular geometrical conditions, along the coil axis the FO8 exhibits a pronounced B_1 spatial selectivity, with higher B_1 field amplitude occurring at some distance from the coil plane [24–26,33]. A theoretical analysis of transverse field RF surface coils, comprising four centrally positioned linear elements, suitable for 0.35 T vertical magnetic fields MRI was described [34]. Transverse field RF surface coils comprising 2, 4 or 6 centrally positioned linear elements were analysed with numerical Finite Element Method (FEM) methods and with MRI imaging at 2.35 T [35]. A careful analysis of circular FO8 coils made by two linear elements was recently reported (Alfonsetti et al., *Measurement* submitted 2009). A comparison of circular loops and transverse field coil design giving the optimal intrinsic SNR was also reported [36]. It was shown that, although for the circular loop there is an analytical equation giving the optimal diameter, unfortunately there is no design rule for the transverse field RF coils. A numerical optimisation method, suitable for 3 T butterfly coils of diameter comprised from 4 to 10 cm and loaded with tissue models, was described [36]. Actively detunable transverse field RF coils were used to enhance sensitivity and compensate RF penetration artefacts for human body MRI at 4 T [37].

Another potential field of application of transverse field RF surface coils is in the study of plasma assisted chemical vapour deposition, which requires an RF plasma source with efficient power transfer and specific deposition homogeneity [38].

Fig. 1 shows schematically a CL and a FO8 coil with diameter $2R$; in Fig. 1 (B) the parameter $2s$ ($0 < 2s < 2R$) is the separation between the linear current elements of the FO8 coil. The tuning and matching circuits, derived from a standard balanced capacitive design [39], are also shown. Tuning

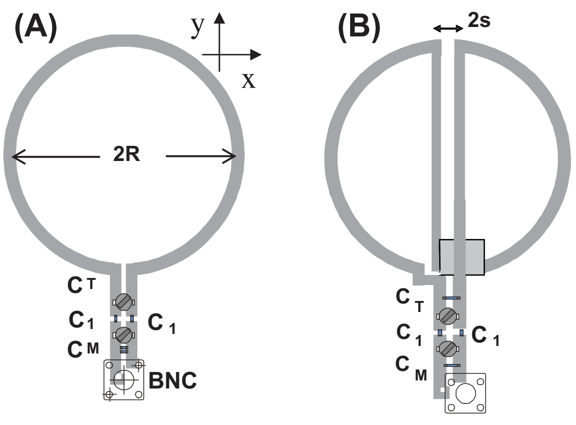

Fig. 1. Schematic construction diagram of the: (A) circular loop (CL) RF coil and (B) figure-of-eight (FO8) RF coil. Tuning (C_T) and matching (C_1, C_M) capacitors are also shown. The diameter of the coils is $2R$ and the separation between the linear elements of the FO8 coil is $2s$.