Receive Arrays and Circuitry

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Introduction

This session provides an overview of the design principles and industrial practice in the modern RF coil design for MR systems.

Receive coils are one of the most challenging components of the MR system, not only from a technical perspective but also because they are one of the few components in direct contact with the patient containing active electronic circuits. The proximity of the coil to the patient is a fundamental aspect in coil design, which is very often only associated to electronic design. During the past 15 years, the rapid expansion of parallel imaging [1] has been facilitated by the development of phased-array surface coils, allowing an optimized signal to noise ratio (SNR) over a large field of view (FOV). The increased number of elements led to an increased amount of electronics in the coil and therefore the need for component miniaturization and for methods to reduce couplings among different circuits. The simultaneous acquisition of the MR signal using an array of surface coils has been proposed by Roemer [2] in 1991 and during the years it has been proven to be competitive with respect to volume coils for both imaging and spectroscopy. This session focuses on the multi-element receive arrays, which are the most commonly used coils in MRI examinations.

Coil Requirement Overview

The design of a receive coil starts with clinical requirements. Requirements can be classified into the following categories:

- Image quality (IQ) performances (e.g. coverage, SNR, parallel imaging capabilities, uniformity)
- Workflow (e.g. ease of use, weight, positioning)
- Patient comfort (e.g. weight, openness, constriction)

Patient safety and compliance to standards are requirements that always *must* be fulfilled by the coil. Robustness of the coil is a requirement that is essential for the coil supplier (to contain costs and increase customer satisfaction) and for the customer. An overview of the primary functions of each coil part is given in Figure 1, it can be noticed that some of the circuits have to fulfill several requirements.

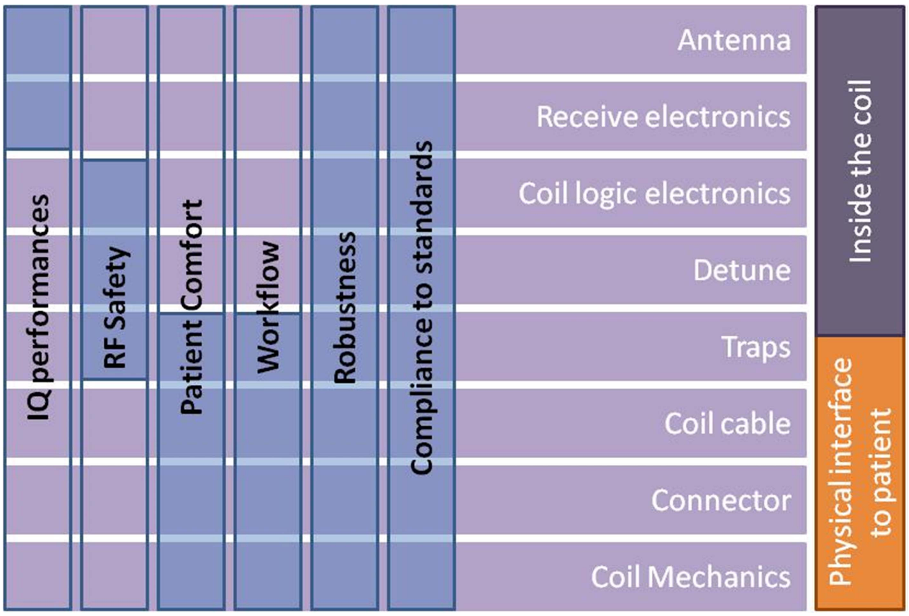

Figure 1: Overview of the primary functions (vertical axis) of each coil part (horizontal). The primary requirements that the coil electronic circuits have to fulfill are marked in dark blue.

Coil Design For IQ Performance

The performance requirements of a coil array are normally expressed in terms of:

- Required coverage of the coil
- Required SNR in the region of interest (ROI)
- Required parallel imaging capabilities

The coil coverage is mainly determined by the physical dimensions of the coil where the antenna conductors are present. The distribution and geometry of the elements in the coils determine the SNR and the parallel image capabilities.

A coil detects the voltage induced by the transverse magnetization of the spins. The coil can be described as a series resonant RLC circuit. The losses are due to the Ohmic losses in the coil and the eddy current losses in the patient that is inductively coupled to the coil [3]. Taking into account the thermal noise generated by the coil and the patient, the SNR of the coil can be written as [4]:

$$SNR \propto \frac{B_1(r)}{\sqrt{4kT(R_c + R_p)\Delta f}}$$

where R_c is the coil resistance, R_p is the resistance equivalent to patient losses generated by the patient tissue in proximity of the coil conductor, B_1 is the spatially dependent RF magnetic field in the patient's tissue received by the coil.

In a single coil design approach, for each given target ROI there is an ideal coil element size: roughly the distance from coil to target equals the diameter of the coil element. Deviation from this ideal size decreases SNR: if the coil element is too large it has more losses (high R_c in the formula above) and it is sensitive to a large part of the patient tissue leading to a large R_p (large effective volume). A too small coil has less noise but it lacks penetration depth (low B_1 in the formula above).

The coil losses are dominant at low magnetic fields while the patient losses are dominant at high fields [4].

Parallel imaging capabilities require a number of coil elements with different sensitivity for each point of the ROI in order to be able to encode the signal. However, by increasing the element density, the electronic losses increase due to the coil element size and the amount of electronics present in the coil. Therefore, the coil design becomes more complex: coupling among elements is more severe, parasitic resonance loops might be created, the amount of cables and cable traps increase and also their possible interaction with the coil elements. A good design balances the needs for accelerated imaging, SNR performance, coil complexity, robustness and costs.

Despite the increased complexity and costs associated with, so called, high density array coils, the number of elements in receive arrays has steadily increased during the past 15 years. Commercially, arrays of 32 channels are available for head and torso. Recently, arrays with 96-elements for head application [5] and 128-elements for torso [6] have been built for research investigation.

Key for the development of a high density element coil is a good strategy for element decoupling. As common practice, receive arrays rely on capacitive or inductive decoupling (via passive components or overlap) for elements close to each other and preamplifier decoupling for other elements. The principle of preamplifier decoupling [2] is based on the principle that the combination of preamplifier and matching circuit creates a high impedance location on the coil element and therefore the current induced by coupling cannot longer flow in the loop.

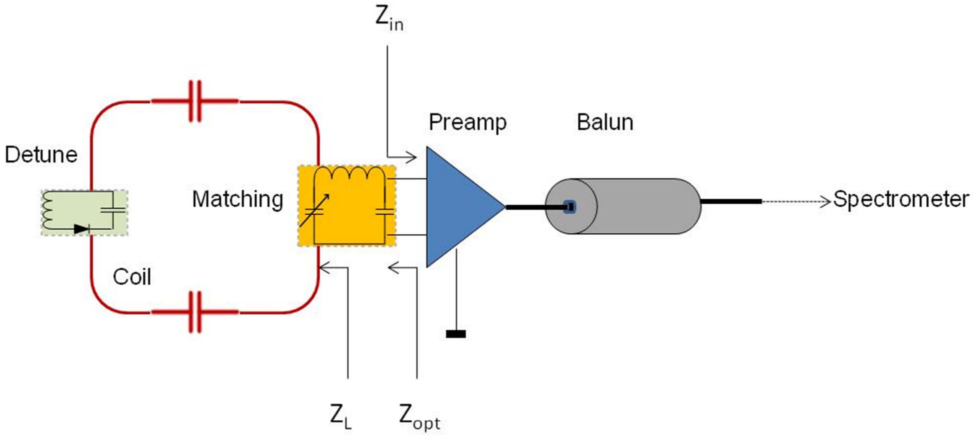

Figure 2: Traditional coil element with matching circuit, preamplifier, detune and balun.

Figure 2 shows the schematic of a receive element with the receive electronics which is commonly placed in the antenna (matching and preamplifier) and the RF safety circuitry in the coil (detune and balun/trap).

The matching circuit has a double function in a multi-element array coil: 1) it offers to the amplifier the optimal impedance for minimal noise figure (NF) and 2) it generates a high impedance point on the coil element in order to minimize the current due to coupling with other elements. Since the matching is located between the coil and the preamplifier, the components have to be chosen carefully in order to minimize the losses which contribute to enhance the noise figure.

As common practice, the design of multi-element coils is based on a single coil approach: each element is matched to the preamplifier separately to the optimal impedance of the preamplifier Z_{opt}, independently from the other elements of the array. An optimization of SNR is achievable by matching the preamplifier to the effective antenna impedance (which includes coupling among elements) rather than to a single element [7], keeping into account the presence of coupling among the array elements.

The enabling technology for high density coils has been the development of low noise high impedance preamplifiers. In order to be able to decouple the elements, the ratio between input impedance Z_{in} and optimal impedance for noise matching Z_{opt} has to be very high or low. High or low input impedance preamplifiers typically make use of GaAs FET (Field Effect Transistor) in the first stage. This guarantees high input impedance and low noise figure. Recent works [8, 9] show that noise figure and gain in a semiconductor are also affected by the strength and orientation of the static magnetic field.

RF Safety

During RF excitation, the coil should withstand the RF field and should not influence the B_1 field distribution. If the receive coil is not “transparent” for the transmit field, the local SAR might be exceeded and/or the electronics might get damaged due to high current flowing in the circuits. The detuning circuits of the coil elements ensure that RF induced currents are blocked during the transmit phase. The detuning of the coil is realized by using pin diodes. There are several detuning possible:

1) Serial detuning: the pin diode is located in series with the conductor of the coil loop. This approach requires high voltage bias in the coil, since the applied voltage to forward bias the pin diode has to exceed the induced voltage on the coil during transmit. The series detuning is broadband.
2) Parallel detuning: the pin diode is part of a resonant circuit in parallel to the coil conductor. This circuit creates a high impedance point on the loop when the pin diode is forward biased (Figure 2). The parallel detuning is narrow band and therefore it detunes only over a certain frequency range.

As safety measure, coils are also provided with passive detuning mechanisms like fuse or passive detuning, in case of system failure of undetected broken components in the detune circuit. This is also required for standard compliance.

In order to make also the RF cables of the coil “transparent” to the RF field generated by the system body coil, traps are used to prevent common mode current. The traps are resonant circuits which create a high impedance point on the cable and they block the propagation of standing waves.

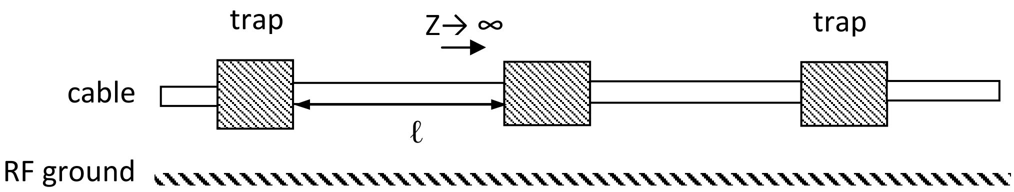

Figure 3: Schematic view of a cable with traps.

In general, in a trap $R_p = Q \cdot Z_0$ (with $Z_0 = \sqrt{L}/\sqrt{C}$) is the parameter that defines the trapping efficiency: high Z_0 (i.e. lower C or higher L) gives more bandwidth, and higher Q gives more attenuation.

Patient Comfort and Workflow

The coil should be easy to use by the operator and it should be well perceived by the patient during the examination. Positioning of the patient is crucial for good image quality. In general, requirements for patient comfort and optimal workflow includes the weight of the coil, the coil dimensions, the cable position, the number and type of connectors, the coil flexibility and geometry. Patient positioning should be easy, coils should not be repositioned several times during examination and the patient should be comfortable to lay down in contact with the coil for the whole MR examination. If the patient is not comfortable, the chance of motion is high at the cost of image quality and eventually efficiency in the examination throughput. The optimal coil element distribution for SNR might not be the best option for the patient. For instance, to reduce the feeling of claustrophobia, the patient should be able to look outside the coil and therefore the coil designer might choose to sacrifice some SNR in order to remove coil elements from the view zone of the patient, improving in this way the patient experience. The coils should also not be uncomfortably tight on the patient because it might prevent patient cooling and cause patient perspiration.

Receive Arrays and Receive Subsystem

In the last few years, the development of high density coils required the availability of an increasing number of receive channels. As a consequence, also the receive subsystem has evolved. Figure 4 shows the evolution for the receive coils and subsystem from an analog receive path (where the spectrometer is located in the technical room (A) or in the examination room (B)) to a fully digital coil (where the spectrometer is located inside the coil) (C) [10, 11]. In the analog system (A and B), the number of receive channels is a property of the system. If the number of coil elements is higher than the number of receive channels available on the system, the coil elements are selected and/or combined. In the digital coil, the receive channels are a property of the coil: the signal of each element is converted to digital by an ADC located close to the coil element. Digitization at the coil more easily facilitates a scalable number of receive channels. This architecture decouples hardware coil design from the cable management in the system since the digital signal is transported via optical fibers.

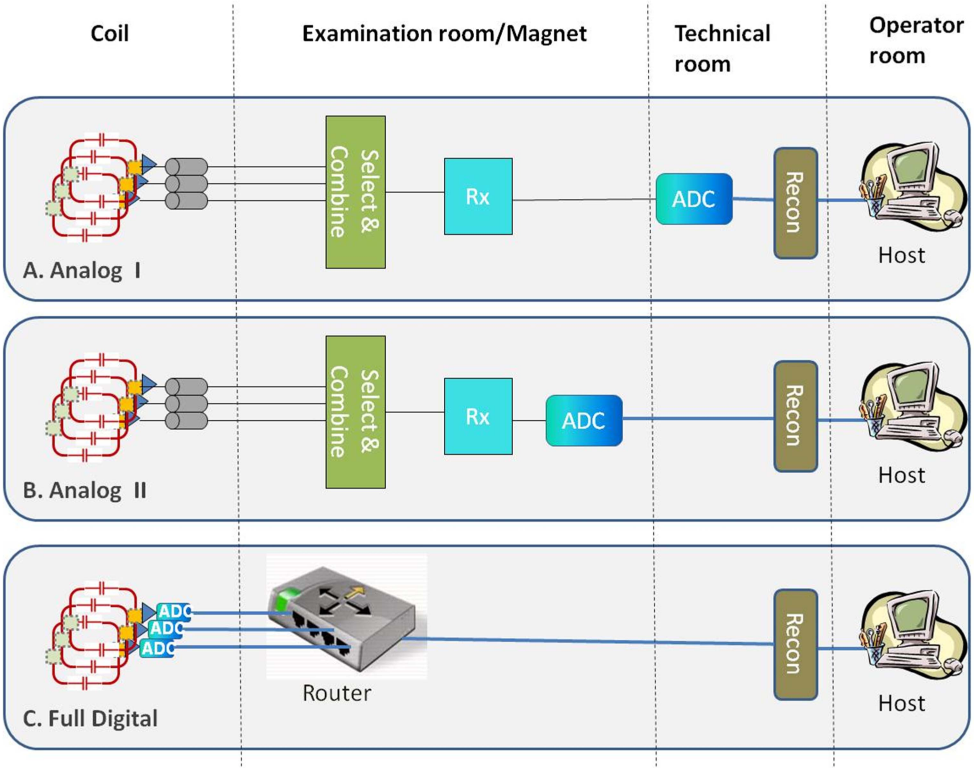

Figure 4: Evolution of the receive chain from an analog concept to fully digital coil.

Summary

This paper provides an overview of the most relevant aspects in multi-element receive coil array design and of the technology evolution of the receive subsystem required to accommodate the need for high element density arrays. The design of a coil should take into account, not only image quality performance, but also reliability, compliance to standards, RF safety, and ease of use. All are as equally important as image quality for a modern MRI system.

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