Coils in 2020

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In attempting to solidify the relationship between "Your Coils and You," it behooves us to give you fair warning of what may remain constant and what is likely to change in that relationship over time. Hence this speculative discussion of what RF coils for MR might look like and what they might be capable of doing by the time we all reach the year 2020. A decade is a long time in technological terms – it can be the equivalent of several generations in a rapidly evolving field. The predictions to follow should be taken, therefore, as nothing more than what they are: highly subjective extrapolations of current trends and exciting recent developments in the area of RF coil design and application. In the end, of course, the ultimate uses to which RF coils will be put are up to you...

What will coils look like in 2020?

For the purposes of this presentation, we will make an arguably arbitrary but conceptually valuable distinction between "low to moderate" magnetic field strengths and "high" magnetic field strengths. The dividing line between these somewhat fuzzy categories will not be based on historical definitions, which have a way of shifting over time. (1.5 Tesla fields, for example, were once considered almost inaccessibly high for MRI.) Instead, we will define "low to moderate" B_0 fields as those for which electromagnetic fields oscillating at the corresponding Larmor frequency are not perturbed in a profound way by the presence or absence of tissue. In other words, at low B_0 field strength, the shape of coil sensitivity patterns is largely independent of the presence, absence, geometry, or content of the body, and RF coil designs may be evaluated in relatively general terms based on how much noise they pick up for any given level of signal or degree of spatial encoding they provide. RF fields at "high" Larmor frequency, on the other hand, are noticeably and substantially distorted by the properties of particular tissues. This certainly holds true for most cases of human imaging at 7T and above, and it may also apply for certain body imaging applications at 3T. Indeed, though the degree of RF field perturbation by tissue varies rather smoothly with frequency and depends upon both the volume and the content of tissue with which coils interact, for our purposes the dividing line between "low" and "high" field strengths may fairly be drawn somewhere in the vicinity of 3T.

It may be shown that RF coil array designs for low to moderate field strength have advanced to the point that further dramatic improvements in performance are unlikely, barring the discovery of entirely new materials or signal detection mechanisms. Various studies over the past decade or so have shown that certain basic coil types can approach the "ultimate intrinsic signal to noise ratio (SNR)," or, in other words, the highest SNR allowed by fundamental principles of electrodynamics [1-3]. Here we will show how these basic coil types (e.g. quadrature volume and surface coils) are actually relatively good approximations of ideal current patterns corresponding to the ultimate intrinsic SNR [4]. We will also show that a

sufficient number of well-constructed loop coil elements disposed around a body may be combined to yield nearly optimal performance [5]. Future development of RF coils for use at low to moderate field strength, then, is most likely to involve matters such as the selection and placement of coil elements and the ease of use of coil arrays. One ongoing trend in commercial coil design is an increasing integration of large arrays of coils, through incorporation into scanner structures such as the patient bed or through development of linked sets of elements which may be combined with ease to access multiple body regions. In this case, increases in the number of coils elements are being driven at least as much by workflow as by performance or parallel imaging acceleration capability. Lightly tethered designs are being explored, and the profusion of special-case coils is beginning to be offset by the development of comprehensive coil sets for broad classes of applications.

Though some similar trends may eventually be expected to take hold at high field strength, a great deal of fundamental work remains to be done in the area of high-field coil design. Even relatively large arrays of loop coils do not approach the ultimate intrinsic limits of SNR at high field, and this performance headroom suggests that new coil designs will be required to capture all the many potential benefits of high field strength. Indeed, we will show how ideal current patterns at high Larmor frequency begin to deviate significantly from familiar loop and volume coil designs [4]. Non-looping "electric dipole" patterns will likely have an increasingly important role to play, and the effective incorporation of these nontraditional structures into the MR setting will challenge RF engineers and physicists in times to come. Additional mechanisms of transmission and detection, such as the propagation of "traveling waves" along the scanner bore and through the body [6], also begin to come into the picture at high field strength, and these mechanisms must be accounted for in any complete assessment of coil performance. What will this all mean for future designers and users of high-field coils? In all likelihood, it will mean that RF coils will become more complex before their use can become any simpler or more effective. Given the complexity of coil-tissue interactions at high frequency, it may well become necessary to combine not only multiple instances of one type of coil element, but also multiple different types of coil elements (loops, strips, directional antennas, etc) in order to maximize performance. It is becoming increasingly clear as well that arrays of distinct transmit coil elements will take their place alongside traditional receive coil arrays in optimizing RF performance at high field strength.

What will coils do in 2020?

Parallel excitation techniques, or the use of multiple coil elements or ports to shape RF excitation, have seen a surge of interest in the high-field imaging community, since they represent one of the most versatile ways of controlling the interaction of RF fields with tissue. The ability to combine multiple transmit coils with distinct amplitudes and phases – commonly called RF shimming – allows coils to be effectively redesigned patient-by-patient and body-region-by-body-region, filling in unwanted signal voids, avoiding unwanted hot spots, in short overcoming some of the inhomogeneity in transmission patterns which is characteristic of high-field imaging. The further freedom to send distinct time-varying RF pulse waveforms to distinct

coil elements – an approach now commonly referred to by the more general term of parallel transmission – enables more targeted shaping of excitation patterns with reduced pulse durations, and with potentially reduced RF energy deposition, as quantified by specific absorption rate (SAR) [7,8]. As things now stand, we have some way to go yet until generalized parallel transmission approaches become straightforward to use: multiple stages of calibration and user interaction are currently required, beyond what is called for in traditional imaging studies with single-element transmission. However, it is widely recognized that some form of parallel transmission is likely to be required for robust body imaging at 7T and above, and an increasing number of ultra-high-field systems are now equipped with parallel transmission capability. Meanwhile, the first 3T systems with at least rudimentary parallel transmission capabilities have already begun to appear on the market. This trend is likely to continue, because the potential value of parallel transmission goes beyond just fixing problems associated with high-field imaging. The control it affords over transmission patterns raises the prospect of creating tailored excitations shaped to particular anatomical regions of interest, eliminating classic problems of foldover into small fields of view and potentially enabling imaging at previously inaccessible speeds and levels of detail. Indeed, the use of many transmitter elements operating in tandem at relatively high frequency calls to mind the analogy of radar, in which phased arrays of elements are used to steer electromagnetic beams with exquisite control. It is not entirely idle to imagine that in 2020 our MR scanners may be equipped with a kind of MR radar.

The story does not end there. If we look closely enough, our coils may have still more surprises in store for us. The presence of interactions between RF fields and tissue is clearly a stumbling block for high-field MR, but, when viewed from another perspective, it may be seen not as an obstacle at all but rather as an opportunity. Whereas at low frequency all bodies look to same to our coils, at high frequency each body makes a distinct imprint upon the electromagnetic field patterns of those coils. Might one in fact try to gain concrete information about the body by characterizing those patterns? The answer, as it happens, is yes. Recently, it has been shown that noninvasive maps of the distribution of electrical properties of tissue – the electrical conductivity and permittivity – may be derived, under certain simplifying assumptions, from maps of the curvature of RF transmit fields observed in MR imaging experiments [9]. In the final part of this presentation, we will survey current efforts to derive electrical property maps directly from MR data. We will conclude by outlining a new approach recently developed at our Center in which arrays of transmit and receive coils are used together to enable generalized electrical property mapping at arbitrary field strength. This burgeoning area of study represents yet another manifestation of the power of multiple coils working together, and of the information-richness of the RF fields which we seek to shape to our purposes in MR. A decade is a long time in technological terms, and we will need it: there is still much left to do!

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