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MRI INSTRUMENTATION - PART II

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I. Introduction

Magnetic resonance imaging has been used clinically for approximately ten years. In this time period systems have evolved and techniques have been developed which have required advances in instrumentation. The purpose of this lecture is to describe what some of these advances have been, and what might be anticipated in the future.

II. The Magnet

The pulse sequences which continue to be the clinical workhorse are those which are based on the RF-refocussed spin-echo technique. With this classic approach any dephasing of spins which occurs after the initial nutation is refocussed by a 180° pulse. In particular, the sensitivity to inhomogeneities in magnetic field is essentially eliminated. However, a major area of development in the last two years is that of high speed imaging. Many of these approaches rely upon gradient-refocussed echoes. In this case there is no intrinsic compensation for magnetic field inhomogeneities and consequently it is desirable to make the magnetic field as uniform as possible. This specification on homogeneity is even more pronounced with echo planar techniques in which the echo train may have a duration of 30 msec, and it is over this period that any signal reduction due to dephasing is undesirable. Accordingly, various methods for automatic shimming have been developed, and it is not uncommon to shim the magnet individually for each patient. For these fast scanning methods shims of a fraction of one part per million (ppm) are required.

Another area of modern magnet development is a more practical one, and that is helium recovery. Rather than permit boiloff of the helium from the cryogen of the superconducting magnet at a rate of one liter every two hours, a pumping technique has been devised in which the liquid helium is continuously chilled below its boiling point. This can cut the boiloff rate considerably.

III. MR Signal Creation

Gradients. Gradients have always been important in the process of spatially encoding the NMR signal for the formation of an image. However, as imaging techniques are further refined, the importance of good gradients becomes even greater. This is true for standard imaging, for new applications of MRI, and for high speed imaging.

By "standard" MR imaging we mean the imaging which employs RF-refocussed spin echoes with TR times of 250 msec or higher. One of the techniques that was developed several years ago was the method of gradient moment nulling or flow compensation. With this method not only the 0^{th} but also the 1^{st} temporal moment of the slice select or frequency encoding gradient waveform is set to zero. This constraint requires that an extra lobe be applied to these waveforms, and for a fixed small echo time of say 20 msec or less, this will increase the gradient duty cycle. An additional development in standard imaging is the use of custom designed RF pulses which require that the slice selecting gradient be varied as the pulse is being applied. This places critical constraints on gradient timing and amplitude.

New applications in MR imaging have also placed increased demands on the gradient system. The first is in vascular imaging. In one technique bipolar gradients are applied along the x, y, or z direction so that blood flowing in that direction acquires an additional phase. As the velocity of the blood diminishes, the gradient amplitude required for a given phase accumulation increases. Another technique employs the time-of-flight concept in which blood incoming to a slice, due to its full magnetization, provides high signal intensity. With this method it is desired to have echo times be as short as possible, and to do this requires rapidly switching the readout gradient to refocus the gradient-recalled echo. Finally, another application is the imaging of diffusion. In this case a subtle reduction in signal may be generated due to the random movement of spins during the application of a gradient. Large amplitude long duration (tens of msec) are required for suitable diffusion encoding.

Finally, fast imaging techniques in MRI have placed increased demands on the gradient system. The two general classes of such methods are echo-planar imaging (EPI) and ultra-short TR gradient echo methods. In the EPI case it is necessary to rapidly acquire 64 or more lines of data in times of about 30 msec. This forces gradient amplitudes of the order of 4 Gauss/cm with switching times of 100 μsec or less. Workers in this area have resorted to resonant coil technology to attain these specifications. In the case of ultra-short TR times it is desired to have the TR interval and the echo time be as short as possible for good temporal resolution. The result is that during essentially the entire TR interval some gradient - either x, y, or z - is energized. In this instance the "ramp" time for energizing a gradient from zero to some desired value becomes important. For example, with five such ramps during a TR interval, a 500 μsec ramp will result in 2.5 msec of the 7.0 msec total TR being used for nothing but energizing gradients.

Radiofrequency (RF) Amplifier/Coil. Recent developments in MR imaging have placed additional requirements on the RF subsystem that were not envisioned eight years ago. One of these is precise control of the phase of the RF pulses. With standard imaging, the same pulse sequence is applied for 128 or more cycles of the acquisition, the only variable being the amplitude of the phase encoding gradient. With newer techniques, by incrementing the phase of the RF each repetition it is possible to shift the image within the field of view. If the field of view is sufficient, it is even possible to acquire multiple slices within one field of view. This provides an improvement in SNR for a given time.

The same concept of control of the RF phase is also important in the method of "RF spoiling." Spoiling refers to the method of dephasing or somehow reducing the sensitivity to transverse magnetization which is residual from previous cycles of the acquisition. Conventionally this has been performed via application of gradients. However, a more effective way of doing this is to vary the phase of the RF pulse from cycle to cycle in a manner which minimizes this sensitivity. Again, this technique requires precise control of the RF phase.

Finally, a substantial amount of work has been performed in the last several years in designing RF pulses. This includes more sophisticated means for amplitude or frequency modulating the RF. This control is required in conjunction with the method described earlier of controllably varying the slice selection gradient waveform during application of the RF.

Master Sequencer. The master sequencer was described previously as that subsystem which controls and synchronizes the signals to all other subsystems involved in the data acquisition. In the past this has involved presetting the acquisition parameters and then initiating the scan. With modern developments in MR imaging this role is expected to expand. Specifically, the concept of "interactive MRI" has recently been demonstrated. In this case the operator varies some parameter of the acquisition while he is observing the reconstructed image sequence. With a feedback time of 1 second or less it is possible to interactively tune some parameter of the acquisition in real time. This requires that the master sequencer accept data from the operator while the scan is in progress and that parameters which govern the sequence be changed during the acquisition, typically between repetitions.

IV. MR Image Formation

RF Receiver Coil/Preamp. One of the possible limitations of MRI is limited field of view (FOV). For example, in spine imaging it is desired to obtain a complete set of images along the entire spine in one scan, rather than image segments of the spine (e.g. cervical, thoracic, etc) sequentially. One of the recent developments which has addressed this is the use of an array of receiver coils. Here the coils are placed side by side along the spine and in one scan the FOV can be extended with no reduction in spatial resolution compared to that obtained with only one coil. In order to obtain the benefits of averaging it is necessary to have a separate preamp/digitizer channel for each of the elements of the coil array. In another application this methodology can be applied to improvement in SNR by causing the coils to view the same field of view.

Demodulator/Digitizer. With standard imaging five years ago all echoes from all pulse sequences were typically sampled at some given rate such as 32 kHz. However, in the interim we have seen the development on the one hand of reduced bandwidth techniques for improved SNR, and on the other hand increased bandwidth requirements in fast scanning methods. To address this desire for flexibility in data sampling system designers have recently turned to "all digital" filter/digitization systems. Typically the received signal is now sampled at several times the highest net digitization rate required, e.g. 256 kHz. Then, depending upon the application, this sampled data is then subjected to a digital filter which provides output at the desired net sampling rate and bandwidth. The result is that one digitally controlled apparatus can be used for all applications.

Storage and Reconstruction. When methods are being devised for the first time it is necessary to first prove feasibility. It is always desired in diagnostic medical imaging that the image formation process be efficient. Recently 3DFT methods have been demonstrated as being effective in a variety of applications. However, such reconstructions are time consuming. However, the overall efficiency of this method can be improved by causing the reconstruction process to commence before the end of acquisition. In this case the data storage must be multiply ported to allow for concurrent reading and writing.

Additionally the field of MRI is moving into the area of realtime interactive imaging. In conjunction with fast scanning methods the reconstruction is performed instantaneously and continuously. Special purpose hardware enables direct loading into the array processor of raw data immediately after digitization. Similarly, interfaces are now used which enable the operator to directly modify the pulse sequence used in acquisition.

V. Summary

Improvements continue to be made in the refinement of MR imaging techniques and the development of new applications. As these become clinically acceptable the instrumentation used for MR imaging becomes more sophisticated. It is expected that such refinement will continue, thereby expanding the applications of MR even further than they are today.