The Future of Neurologic MR Imaging

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AJNR Am J Neuroradiol 2000, 21 (1) 37-40
http://www.ajnr.org/content/21/1/37

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One of the features that has characterized magnetic resonance since its first demonstration in 1946 has been its ability to reinvent itself and develop in new and surprising ways. One such change was the development of MR imaging; this technique has evolved in unpredictable directions.

We will assume that the laws of physics, chemistry, engineering, biology, and, to a lesser extent, economics will not undergo any fundamental change in the foreseeable future, although anyone who had assumed this in the year 1900 would soon discover that s/he was mistaken. We will assume that there will be no shortage of clinical imagination in applying techniques so that the limitations specific to MR imaging are likely to arise from the physical, chemical, engineering, biological, and economic constraints of the technique itself. These will be expressed in achievable machine design and performance, which will form the focus of this discussion.

Image Content

As with plain radiology, the basic appearance of most images that radiologists use for diagnostics may show little fundamental change. It is likely that radiologists in general will continue to rely on T1- and T2-weighted images very comparable with those used today. Special contrast generation methods, such as diffusion weighting and magnetization transfer contrast will be associated with the same range of indications as at present, with extensions. People are likely to be much more interested in first-pass perfusion, diffusion anisotropy, elastography, and other techniques as well as numerical values for all the major parameters (including T1 and T2), blood volumes and flows, and metabolic changes quantified by the differences in spectral peak amplitudes or areas or both.

Progress in the development of new contrast mechanisms may be one of the disappointments. We will get much more data about tissue compliance, more about regional perfusion, and improved localization of metabolic data. Although we will continue to expend significant resources seeking a major clinical role for spectroscopy, it is likely that the method will remain most useful for imaging the CNS of nonfocal disease as a means of confirming the presence of physical disease in neurologic conditions that cannot be characterized otherwise. This may seem to be negative in view of all the effort that has gone into seeking its application to clinical practice, but it follows the pattern already established by its successful use in the brain for monitoring conditions such as hepatic encephalopathy. It is fundamentally a biochemical tool and it is most likely to find a role in diseases of perturbed biochemistry.

The future application of functional MR (fMR) imaging (fMR imaging based on the blood-oxygen-level dependent effect) in clinical practice is less certain. The use of first-pass or arterial spin-tagged perfusion studies will satisfy most requirements, but clinicians such as psychiatrists will continue to strive to develop reliable protocols exploiting its noninvasive nature.

Molecular imaging (in which, for example, MR imaging is used to visualize genetic manipulation) is unlikely to have a substantial impact on clinical practice for many years, though there will be intensive investigation of it. Techniques such as those in which enzymes expressed by genes are inserted into cells and structures as part of therapy-release contrast agents are very exciting research tools, but will only affect patients to a significant degree when the general problems associated the delivery of gene-based therapy are resolved.

Scanner Operation

Technologists may experience much more substantial changes in the way in which scanners operate. They will no longer have to go through the routines of setting up the system, culminating in a series of pilot scans from which their subsequent scans will be determined. Instead, they will simply command the machine to acquire a T1-weighted followed by a T2-weighted volume (except in situations such as brain attack in which the need for minimal patient time in the machine may dictate taking the former only). Though resolution will be 256 × 256 × 256, the time taken to acquire a T1-weighted scan will be 20–25 seconds, and that for the T2-weighted volume perhaps will be 1.5–2 minutes. Even a 256 × 256 × 256-volume sequence using fluid-attenuated inversion recovery will take no more than a few minutes to obtain in most instances. Many users will prefer 512 × 512-volume images (and, even, on occasion 1024 × 1024). These will be much quicker to obtain (so

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that a 512 × 512 × 256-volume T1-weighted data set will be recovered in 50 seconds or so), and improved by the use of more sophisticated gating and motion correction procedures. The extreme ease with which volume data can be acquired will lead to the routine application of MR angiography, and of many other examinations in which several data sets are processed together. Specifically, this will be used for measurement of blood flow, susceptibility effects in hemorrhage (as part of the process of doing all the imaging needed for brain attack investigations and monitoring on one machine), and elastography.

Therapy

Thus far, this commentary has been written very much from the point of view of the present-day radiologist. An issue of much greater potential impact is the extent to which MR imaging will be used at all stages during patient management rather than only during the diagnostic workup. This will ultimately depend on the value this offers to patient treatment, the convenience with which patients can be handled, and implementation cost. MR imaging should be contemplated in this context because of its potential for improved therapeutic accuracy, minimized collateral damage, and accelerated assessment of patient response to the therapy, so that alternative strategies can be implemented as quickly as practicable in the event that the first approach is unsuccessful. Indications thus far are that MR imaging (sometimes in conjunction with MR spectroscopy) is capable of delivering important data in support of all three goals.

Interventional MR imaging ultimately requires a machine with maximal patient access, good performance, ease of use, and reasonable cost—things that may appear to be a contradiction in terms. Provision of machines in the right place for brain attack therapy actually has very similar requirements, with installation in emergency rooms, or even in large ambulances (rather than in the present type of articulated truck).

Higher Static Fields

Monitoring of physiologic function will push machine design toward still higher fields, where the perceived intrinsic signal-to-noise ratio allows accurate detection of smaller transient signals or other changes. There is a case for the use of 3-T or 4-T scanners outside of the research environment of fMR imaging or spectroscopy. The latter, in particular, stands to gain from the greater sensitivity that can be used to track contrast agents and labels such as fluorine 19 and carbon 13. Clearly, macrophages labeled with super paramagnetic iron oxide can be better monitored with improved scanner performance; however, 3-T and 4-T magnets run contrary to other criteria driving MR imaging forward. They cannot be made more open because of constraints on field homogeneity and engineering limits on the superconducting coils. Although magnetic field variations are usually quoted in ppm, most of the effects of poor field are a function of absolute field error, which increases at constant ppm as the field strength increases. Higher field magnets also generally require longer cryostats to accommodate increased amounts of wire both in their primary winding and in the shields of self-shielded designs. The latitude available for increasing the current in the wires is not great, as the current densities in coil windings have already been increased in order to make magnets more compact. A 3-T or 4-T system will necessarily cost more than a 1.5-T magnet, because the rest of the equipment will be at least as expensive, and the magnet cost will become a much more significant fraction of the whole.

Although it is probable that 3-T and 4-T scanners will reach clinical practice, it seems less likely that still higher field systems will. The effects of 7-T and 8-T machines on patients and technicians, which are currently being investigated, suggest that acceptance of higher field systems will be marginal at best. These systems will probably be used for research, though some of the very high-resolution head images they have recently been generating do suggest that information of real clinical importance may arise from them. Even so, potential changes in MR safety guidelines and patient-handling issues related to achieving economical viability militate against widespread use of very high-field systems.

Open Magnets

One of the most interesting aspects of MR imaging in the next few years will be the evolution of current open magnets. These have found widespread acceptance among patients, leading to a significant shift toward lower field use in radiologic practice. Clearly, in the sense that surgeons would really like full and unfettered access to the patient, no machine at present on the market is open. The Signa SP (General Electric; Milwaukee, WI) goes some distance toward the ideal; the various C-magnets go some way also, though in a rather different sense. In particular, the latter tend to offer the chance of better costs and improved compatibility with the rest of an operating room, even though they do not solve the access problem. Cylindrical magnets allow poor access, even allowing for strategies such as moving the magnet to the patient to help with handling the very ill. Intervention in a cylindrical magnet will always involve preparation of the patient outside the magnet prior to his/her location in it, no matter how that is achieved.

Magnets with a field transverse to the patient offer much more potential for the future. Interventional magnets with clear gaps in excess of 1 meter will be developed, though their fields are unlikely to develop much beyond the 0.5- to 0.6-T range. Diametric spherical volumes—the measure of homogeneous volume—will be notably smaller than those commonly used today, as efforts to improve access for clinicians will result in pole diameters smaller than magnet design theory would suggest were desirable. These machines are likely to be iron-yoked, though with cryodrivers rather than the electromagnets or permanent magnets that are usually (but not exclusively) used today. One feature of interventional magnets that will affect their design is that they will have fast-ramp capability and be configured so that machines can be de-energized and brought back into operation in no more than 5 or 6 minutes. This will offer two things of substantial importance to hospitals and surgeons. First, it will allow the facility in which the magnet is installed for ordinary operating room use in circumstances in which imaging is not required, thereby helping with overall costs. Second, it will address the kind of restrictions that are being proposed in Europe in which environmental health regulations being promulgated insist on very low-field doses for those working with machines. With these restrictions, dose is being measured as the product of field and time specified in Tesla hours/day). Worldwide, the regulatory agencies involved with environmental safety are not the same as those concerned with the clinical performance of equipment. Growing concerns about the possible carcinogenic properties of electromagnetic radiation (50–60 Hz fields from the electricity supply, and the microwave emissions from mobile phones in particular), whether well-founded or not, are likely to lead to environmental restrictions becoming a much more important feature of machine design and operation. To illustrate this, the MR imaging community in Germany has recently been dealing with a proposal to respecify the 5-gauss-line round machines as a 3-gauss-line. The worldwide cost of such a change implemented retrospectively has been estimated to be as high as $1 billion.

These limitations will lead to major efforts to maintain the image quality to which users have become accustomed in machines that would otherwise seem inappropriate. This will constitute a change in conventional priorities, because current standards are skewed by the huge effort in research and development that has been applied to 1.5-T systems, making it likely that they will perform best.

Gradients

Improving gradient field quality is the most underrated means of improving overall system performance. Making the best possible gradients for the transverse field machines, with the same sort of operating parameters as in modern cylindrical magnet systems, is likely to be beneficial. In some ways, controlling eddy currents in iron-yoked units is more important even than in cylindrical magnets. Stray fields generate not only the unwanted eddy currents that cause so many problems, but also result in hysteresis effects in the iron that can lead to even more complex and awkward artifacts that militate against good operation. Overall, peak gradient performance is unlikely to change much over the next few years, except in situations where in vivo microscopy is advantageous (most likely in intervention).

Radiofrequency Systems

The same is not likely to be true of radiofrequency (RF) systems. It was suggested in the early days of MR imaging that, because solenoidal receiver coils are more efficient than saddle-type arrangements, vertical-field systems have an intrinsic, quite significant field-for-field signal-to-noise ratio advantage. Today, for systems in which body loading is dominant, quadrature operation is the norm, and many RF coil systems are arrays, the situation is much less clear. All forecasts made toward the start of this commentary were based on the expectation that the use of variants and extensions of encoding techniques exploiting the restricted field of view of small coils will become the norm for signal recovery. These methods (eg, SMASH or SENSE) make use of the parallel channels of information available from modern array-capable scanners to reduce the amount of spatial encoding by gradients that is required. The result will be a reduction of 2, 4, or even more in scan times.

The type of coil structures that are likely to be needed for this are intrinsically easier to implement in magnets with fields parallel to the patient's axis, rather than transverse to it. This is likely to mean that the traditional gain from the latter will actually not be realized. The use of large-array coils may well result in an increased gap between the relative performances of machines operating at different fields. Although it will still be possible to achieve body loading of the coils at higher fields, at lower fields it is more difficult, and serious investigations of the feasibility of using refrigerated copper or superconducting coils will follow. Although such strategies will not overcome the performance gulf completely, they may well reduce it significantly. Such coils will initially be cumbersome and awkward, but they are likely to evolve rapidly into generally acceptable items.

Artifacts

One further factor that will determine the extent to which performance differences are reduced is the presence (or lack) of noise-like artifactual signals (which are, in principle, independent of field level). Most radiologists are aware of the puffy noise associated with imaging of living subjects, and this means that in vitro signal-to-noise ratios are rarely actually achieved in vivo. We would expect that the monitoring of patient position with high accuracy will become a routine part of imaging practice and that the data thus obtained will be used to optimize scanning. Active fiducial markers will be attached to patients externally or even internally as a matter of routine. Such fiducials are tiny and MR-compatible, and permit robust measurement times of a few milliseconds. Their disadvantage is that they can require a cable connection. Fiducials such as these can be used to monitor macroscopic motion such as swallowing, breathing, and, indeed, heart beats, but they can also be used to detect other tiny movements. The data derived from them will be used to correct individual acquisitions. In some patients they may remain attached for repeated examinations; others will simply have them fixed for the duration of their period in the machine. Strategies developed using these, and the volume imaging techniques emphasized previously, mean that the patient positioning and handling will change radically with less concern about precisely where the patient is in the machine or whether s/he remains still. The machine will be relied on to determine patient position and motion.

Image Processing and Data Handling

There will be a much greater emphasis in the future on image processing. Radiologists will expect to manipulate images in complex and sophisticated ways. With increasing availability of local area networks and the internet and with increasing bandwidth communicating channels, remote viewing of image data will become the norm. This will lead to a growth not only in teleradiology of a conventional sort, but also teleconference, e-mails, and other remote communication methods will make specialist expert opinion immediately available. The next generation of mobile phones is predicted to allow image transfer, allowing the radiologist to view high-quality image data wherever they are. The expected explosion in the quantity of data, both from increased acquisition speed and as a result of data fusion with other techniques and image processing, will lead to a reappraisal of archiving. It is probably that data will be loaded to a transient archive, with a radiologist making the decision as to what is finally to be retained and used in reporting.

As mentioned before, quantification will be much more usual, both for MR parameters and for subtle changes in size and shape of tissues. Spatial registration of data will be the norm for any one patient, with data from an initial study being used as baseline, and that from repeat studies being continually aligned. The concept of the continuing examination will develop, in which data acquired at different times and by different techniques will be fused to form a single coherent spatiotemporal patient file. When a patient is admitted to a hospital, it will be possible, with proper safeguards, for all the patient's notes and images to be transferred electronically to it. It may well be that general physicians' offices will hold all patient data, with hospitals anywhere in the world being able to obtain access to them.

Conclusion

In evolutionary terms, if imaging life began with Roentgen in 1985, then there was a Cambrian explosion of new imaging techniques in the 1970s with the development of CT, Doppler sonography, MR imaging positron emission tomography, thermography, electrical impedence tomography, and microwave imaging. We are still living through the consequences of this. In the last century, our understanding of the process of evolution itself has radically changed with new appreciation of its variable rate and the significance of mass extinctions. We should expect the prosaic regarding improved coil and gradient performance as well as the unpredictable with major advances perhaps in areas such as magnetic materials and contrast agent chemistry. Of course, like those who projected the outlook for 20th-century neuroimaging in 1900, we too may be completely surprised by the future.