MAGNETIC RESONANCE MICROSCOPY IN BIOMEDICAL RESEARCH

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Abstract: Magnetic resonance (MR) microscopy is a special modality of MRI with an emphasis on high spatial resolution. While its main principle is identical to conventional clinical MRI, there are several differences between the two that are mainly associated with a use of stronger magnets and gradients. MR microscopy has numerous interesting applications in material and bio sciences in which high spatial resolution is demanded and long experiment times are allowed.

Key words: magnetic resonance imaging, microscopy, SNR, 3D imaging.

Introduction

Magnetic resonance imagining is a well-established method in diagnostic radiology. However, there are other uses of magnetic resonance imaging. One of these is magnetic resonance imaging with an increased spatial resolution, so called magnetic resonance (MR) microscopy, which is gaining importance in material research. MR microscopy does not provide a real microscopic spatial resolution. However, its resolution is still at least ten times higher than that of conventional MRI. If conventional MRI has a resolution of 1 mm then a typical MR microscopy resolution is of the order 10–100 μm. This is not high enough to image a single cell, but is good enough to obtain a precise anatomical image of fine structures of living systems. Typical applications of MR microscopy range from materials (porous materials, cements), plant tissues (stems, branches, seeds, buds), small animals (mice, insects, beetles) to \textit{ex vivo} tissues (teeth, blood clots, cartilage) [1].
Theory

While MR microscopy uses exactly the same imaging principle as conventional clinical MRI and practically all the imaging sequences of clinical MRI are to some extent applicable also to MR microscopy there is also a distinct difference between the two modalities of MRI. These are associated with different signal, noise and gradient regimes.

Signal

An increased spatial resolution of MR microscopy poses heavy demands on MRI hardware especially on MR magnets and gradient probes. For example, a twofold isotropic spatial resolution increase is associated with an eightfold decrease of voxel volume. As the MR signal of the voxel is proportional to its volume the twofold resolution increase results in an eightfold voxel signal decrease. The voxel signal decrease necessitates the use of strong MR magnets. Assuming that the MR signal is proportional to the magnetic field squared, the eightfold signal decrease can be compensated by the use of a 2.8 times stronger magnet. The situation gets worse with increasing resolution and easily leads to a situation when magnets that could compensate signal loss due to the increased resolution are unexciting. Another factor that may influence the MR signal is also the sample temperature. As the nuclear magnetization is inversely proportional to the absolute temperature and the MR signal is proportional to the magnetization, the MR signal is therefore inversely proportional to the absolute sample temperature. Extreme cooling of the sample would therefore highly increase the MR signal. Unfortunately, this option cannot be used in live samples and is practically never used in material MRI as extremely cold samples are solids, while for MRI liquid samples are needed.

Noise

If the MR signal cannot be additionally improved then there is still an option of noise reduction. What is important is not solely the MR signal but its ratio to noise (SNR). An important source of noise is the thermal noise of an RF coil. This is proportional to the square root of the absolute RF coil temperature. Therefore, noise can be reduced by lowering the coil temperature. This option is now routinely used in cryoprobes. Another source of noise is also sample conductivity, which is important only for highly conductive or large samples [2]. SNR can be increased also by signal averaging. In this process the signal increases linearly with the number of averages, while the noise increases as the square root of the number of averages. For example, by four signal averages SNR will be improved by the factor of two. This method can be applied on any system, and is a cheap, but time-consuming alternative to the use of stronger magnets.
Magnetic Field Gradients

In MRI, signal acquisition bandwidth divided by the image size in the readout direction, i.e., the pixel bandwidth, should be larger than spectral line bandwidths and chemical shifts between different spectral lines. If this condition is not met, then the image is blurred (because of line bandwidths) and smeared (because of multiple spectral lines) in the readout direction. Because chemical shifts are proportional to the magnetic field strength, blurring and smearing artifacts in the readout direction can be avoided by increasing the image acquisition bandwidth. The increase has to be proportional to the magnetic field strength increase.

Imaging gradients are proportional to the acquisition bandwidth and are inversely proportional to the field of view. Therefore, in MR microscopy, where resolution and magnetic field strengths are both approximately ten times higher than in typical clinical MRI, magnetic field gradients are up to 100 times higher than in clinical MRI, i.e., of the order of a T/m. Use of strong gradients in MR microscopy is associated with a significant signal loss due to diffusion. Every gradient in MR microscopy imaging sequence practically reaches the amplitude of those that are used in diffusion-weighted imaging (DWI). Therefore, any MR microscopy imaging sequence is in part also a DWI sequence. As the diffusion-weighting increases with the gradient amplitude squared and with the third power of time separation between diffusion encoding gradient pulses [3], the latter is especially true for sequences with long echo times.

Materials and methods

Experiments were done on a 2.35 T (100 MHz proton frequency) high resolution horizontal bore magnet made by Oxford Instruments (Abingdon, UK) and a Tecmag Apollo spectrometer (Houston, USA). The magnet was equipped with a Bruker micro-probe (Ettlingen, Germany) with top gradients of 250 mT/m. The RF probe had an inner diameter of 25 mm and could accommodate samples with sizes up to 20 mm in diameter.

The performance of the system is demonstrated on an extracted molar tooth sample. The sample was imaged using a conventional 3D spin-echo imaging sequence with contrast parameters (TE/TR = 2.4/600 ms), imaging matrix 256 × 128 × 128 and field of view 25 × 12.5 × 12.5 mm³. The image resolution was 100 μm in all three spatial directions.

Results and discussion

Figure 1a shows four 3D volume rendered images 90° apart around the vertical axis of a molar dental pulp. The images were reconstructed in post-pro...
cessing from a stack of 2D images that corresponded to individual sagittal slices across the tooth; 32 of a total of 128 are shown in Fig. 1b. The entire tooth was imaged, however only the dental pulp produced a detectable MR signal. Hard dental tissues (dentin and enamel) were not detectable by the MRI sequence used as they have too short relaxation times.

Figure 1 – Volume rendered images (a) and a corresponding sequence of 2D images of a dental pulp

Conclusion

MR microscopy is an excellent tool for achieving high spatial resolution with a good contrast. It can be used for materials or biological samples that allow long scan times.
REFERENCES


Резиме

МИКРОСКОПИЈА СО МАГНЕТНА РЕЗОНАНСА ВО БИОМЕДИЦИНСКИ ИСТРАЖУВАЊА

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Апстракт: Магнетно резонантната (МР) микроскопија е МР техника со акцент на високата просторна резолуција. Дадео главните принципи на МР микроскопијата се идентични со они на конвенционалното клиничко снимање со магнетна резонанса, постојат неколку разлики помеѓу овие два модалитети, кои најчесто се поврзани со употребата на посилни магнети и градиенти. МР микроскопијата има бројни интересен апликации и примени во хемиските и билошките науки, каде што високата просторна резолуција е нужност, и каде што е дозволено експериментите да траат долг временски период.

Ключни зборови: имацинг со магнетна резонанса, микроскопија, сразмер помеѓу сигналот и шумот, 3-димензионално снимање.

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