Homogeneity Spoil Spectroscopy as a Tool of Spectrum Localization for *in Vivo* Spectroscopy

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In vivo spectroscopy of ^{31}P provides insight into the energy metabolism of living tissue. It is, therefore, an important tool in the assessment of the metabolic state and offers various applications ranging from the diagnosis of muscle diseases (1-3) to examinations of brain metabolism in newborn infants (4) and therapy control in tumor treatment (5). Since T_2 of ^{31}P *in vivo* is short (several tens of milliseconds), the application of localization techniques, which require even a short time interval between excitation and acquisition, is gravely restricted. This fact and the low signal/noise ratio of *in vivo* ^{31}P spectra caused by the low tissue concentration of ^{31}P have made surface coil spectroscopy (6) the main tool for clinical ^{31}P spectroscopy.

Several ways have been proposed to deal with the ill-defined sensitive volume caused by the complicated profile of the exciting radiofrequency field B_1 around the coil (7, 8). The major problem for practical applications is the high intensity of signal from tissue lying directly adjacent to the surface coil. Since muscle tissue lying under the subcutaneous fat has a comparatively high phosphorus content, the corresponding signal in many cases masks the spectra of interest, such as those from deeper structures, and prohibits a quantitative analysis of signal intensities. This and the need to have a technique which reliably allows measurement of spectra under identical conditions with a high reproducibility for long-term studies have led us to develop a method which maintains the simplicity of the surface coil experiment but still eliminates unwanted signals from subcutaneous tissue.

The basic concept of our method is related to the principle of topical magnetic resonance (9) and to that proposed by Crowley *et al.* (10), using field inhomogeneities to destroy the coherence of unwanted signals. Since we wish to combine the spectroscopic experiment with an imaging examination in a magnet system with very high basic field homogeneity, a minimum of additional hardware can be employed to generate the homogeneity-spoil effect. We have found the introduction of a thin sheet of adhesive plastic dotted with an appropriate number of fine particles of ferromagnetic material to be a practicable solution for our purpose.

The line of a resonance is broadened by field inhomogeneities, leading to a decreased height of the line and to the possibility of filtering out unwanted signals. A field in-

FIG. 1. Theoretical estimates of the field profile for the z component as a function of the perpendicular distance (r) to (A) a straight wire along with the x axis; (B) a sheet, moderately dotted with two to three ferromagnetic particles per squared centimeter; (C) slightly dotted sheet (half the density as in (B)); and (D) one ferromagnetic particle (magnetic dipole). All curves are normalized to 1 at $r = 5$ mm.

homogeneity (B'_x, B'_y, B'_z) adds to the main field B_0 (in the z direction) to give an effective B'_{eff} :

$$B'_{\text{eff}} = \sqrt{B'^2_x + B'^2_y + (B_0 + B'_z)^2}. \quad [1]$$

It is a reasonable assumption that the inhomogeneity is several orders of magnitude smaller than B_0 ; therefore, the contribution of the transverse components of the inhomogeneity is negligible in comparison with $(B_0 + B'_z)$. Thus, only the z component of inhomogeneity contributes to a measurable effect on the resonance frequency:

$$B_{\text{eff}} = B_0 + B'_z. \quad [2]$$

In order to eliminate signals arising from the surface without affecting the linewidth of deeper signals, it is necessary to find a field profile which depends strongly on the distance from the surface. In a small gap, naturally produced by the skull or as a characteristic of a surface coil between 90° and 270° pulses, the inhomogeneity should fall stepwise from high values near the surface to negligible ones in the interior. For a pointlike ferromagnetic material introduced into a magnetic field, the z component along the x axis can be calculated (Fig. 1) for a distance r by

$$B'_z = \text{const} \times 1/r^3. \quad [3]$$

Because of the rotational symmetry, the same dependence is correct for the z component of any transverse direction.

Numerical summation of arrays with different amounts of dotted ferromagnetic dipoles gives further insight into the possibilities and limitations of this arrangement (Fig. 1). For a sheet of ferromagnetic dipoles lying in the xz plane, the z component of the field (along the y axis, through the center of one dipole) is numerically calculated. Slightly dotted sheets show behavior similar to the single dipole, but, with increasing

density, one gets a less pronounced slope. This seems to be the upper limitation for the dotting and for the control of the influence in deeper zones.

On the other hand, for a conducting wire (e.g., a circular loop), it is important for our purpose not to calculate the component perpendicular to the plane of the wire (e.g., xz plane), but the z component of the magnetic field. This z component in a distance r can easily be estimated for a straight wire along the x axis (Fig. 1):

$$B'_z = \text{const} \times 1/r. \quad [4]$$

The off-axis dependence of the magnetic field of a circular loop lying in the xz plane cannot be solved analytically. Numerical calculation of the resulting elliptical integrals shows that the z component of the field has a similar flat behavior near the wire (distance to the wire smaller than the diameter of the loop) as the single straight wire (Fig. 1). In addition, there is a plane with no z field component in the center of the circular loop.

With this estimation, one can see the difference between ferromagnetically and electrically produced z components of magnetic fields in an existing B_0 . Equations [3] and [4] show in principle the higher performance of a dipole for the required steep slope of the inhomogeneity. Because we want a well-defined distinction between surface and interior, a maximal gradient is required, which can be better produced by a ferromagnetically dotted sheet. On the other hand, there are limitations for the density of the grains of a ferromagnetically dotted sheet.

The sheet with the optimal effect was found empirically. The influence on the homogeneity can be demonstrated (Fig. 2) with a gradient-echo proton-imaging experiment (11). In this experiment, echo refocusing using reversed gradients does not occur for inhomogeneities of the field, which are not reversed during the experiment. Figures

FIG. 2. Demonstration of the influence of inhomogeneity on a ^1H gradient-echo-imaging experiment (11) at 100 MHz with a repetition time (T_R) of 37 ms and an echo time (T_E) of 15 ms. On the left-hand side, without, on the right, with, a ferromagnetically dotted sheet below a tank of water.

FIG. 3. (a) ^{31}P spectra at 40.5 MHz from a two-compartment phantom with a 5 mm thick compartment close to the surface coil containing 5'-AMP and, separated by a Plexiglas plate of 2 mm, the main chamber of the phantom filled with NaH_2PO_4 . (b) Same experiment with a ferromagnetically dotted sheet between surface coil and phantom. (c) Same as (b), but with a composite pulse sequence (8) for further discrimination of unwanted signals from the surface. This also illustrates the possible combination with other methods. Spectra were obtained with 16 scans and a delay of 2.5 s.

3a, 3b, and 3c show ^{31}P spectra from a phantom with two compartments. The phantom was designed to simulate the salient features for brain spectroscopy. A flat outer compartment with a thickness of 5 mm supposed to simulate subcutaneous tissue contained

FIG. 4. Signal intensities of ^{31}P resonances at 40.5 MHz of the same phantom as in Fig. 3 as a function of pulse length. The solution on the surface (1B) shows a 90° pulse at about 40 microseconds whereas the signals from the deeper lying phosphorus (1A) have their maximum at about 80 microseconds. (2A and 2B) The same experiment performed after placing the ferromagnetically dotted sheet directly between the surface coil and the phantom. For all pulse lengths, the signal from the flat compartment vanishes (2B), while the signal from the main chamber of the phantom (2A) shows a similar dependence on pulse length as without the sheet. A decrease of the peak height caused by a slight broadening of the line is less prominent at longer pulse widths with an increased contribution from deeper lying regions to the signal.

a solution of 100 mM 5'-AMP in H₂O at pH 7.9. The main chamber of the phantom was separated from this solution by a plate of 2 mm thickness and was filled with 120 mM NaH₂PO₄ in H₂O at pH 4.3. Spectra were acquired in single-coil technique with a flat surface coil of 55 mm diameter. Figure 4 shows the resulting signal intensities as a function of the excitation field B_1 . The change in flip angle with increasing pulse length is faster in the flat compartment (curve 1B) than in the main chamber of the phantom (1A). Curves 2A/2B in Fig. 4 show the same experiment performed after placing the homogeneity-spoil sheet directly between the surface coil and the phantom. The signal from the flat compartment vanishes irrespective of the pulse length (2B), while the resonance from the main chamber of the phantom (2A) shows only a slight increase of the linewidth, resulting in a decreased intensity.

All experiments have been performed on a Bruker 24/40 system at 2.35 T.

Placing a ferromagnetically dotted plastic foil between a surface coil and the body offers a convenient way to avoid contamination of spectra from deeper lying tissue by signals arising from subcutaneous tissue close to the surface coil. Due to its simplicity, this method can be used on any NMR system. The high reproducibility of this technique allows its application for long-term studies, e.g., for therapy control. Since this method for localization does not interfere with the actual NMR experiment, it can be applied in combination with more demanding spectroscopic techniques for ¹H or ¹³C spectroscopy.

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