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Spatial Localization of NMR Signals by Narrowband Inversion

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Surface coils for exciting and detecting NMR signals are often used in place of the traditional solenoid or Helmholtz coils in situations where only a small region of a large sample is of interest (*1*). In particular, this is the situation in many *in vivo* studies (*1–5*). Typically, it is desirable to observe signals from a single organ without interference from the surrounding tissue. The degree of spatial localization achieved with a surface coil in a single-pulse experiment is often insufficient, however, requiring that the organ be surgically exposed (*6–9*). A unique characteristic of a surface coil is the fact that it produces a very inhomogeneous radio frequency field within the sample. In general terms, the rf amplitude decreases with distance from the coil (*1*). This suggests the possibility that a higher degree of spatial localization may be achieved with surface coils if the signals are excited by a pulse sequence that is inherently very sensitive to rf amplitude (*10–18*).

We have recently developed rf pulse sequences that invert nuclear spin populations only over a narrow range of rf amplitudes (*18*). We call such sequences narrowband inversion sequences. They are similar in form, although opposite in function, to the composite pulses for broadband inversion originally proposed by Levitt and Freeman (*19–24*). With a surface coil, a narrowband inversion sequence inverts spins in a small region in space. Here we propose an experimental method that exploits narrowband inversion in conjunction with surface coils to produce spatial localization of NMR signals. We call the method NOBLE (Narrowband for Localization of Excitation).

Let P be a narrowband inversion sequence and R be a "read" pulse or pulse sequence. As illustrated in Fig. 1, NOBLE consists of the following steps:

(1) Digitize and store the FID following R alone, as in Fig. 1a.

(2) Digitize and store the FID following the sequence of Fig. 1b(i). τ is a delay during which residual transverse magnetization dephases. A static field gradient may be required during the delay. In the FID, signals arising from the spatial region in which P inverts spin are themselves inverted.

(3) Subtract the FID of step 2 from that of step 1. Only spins inverted by P contribute to the remaining signal.

The need for a pulsed field gradient may be eliminated by a variant of NOBLE:

(1′) Digitize and store two FIDs following R alone.

(2′) Digitize and store two FIDs from the sequence in Fig. 1b(ii). The notation P_ϕ indicates that the overall rf phase of P is cycled between 0 and π.

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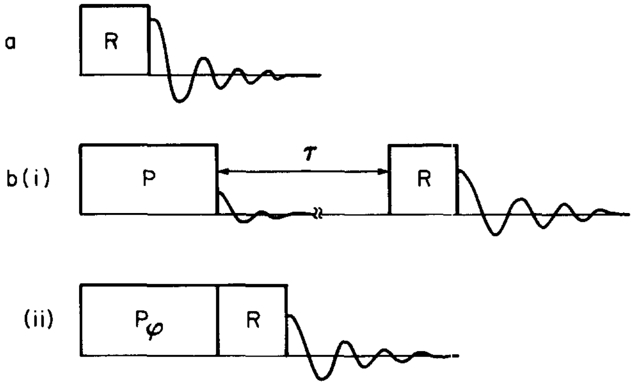

FIG. 1. Schematic representation of NOBLE. P is a narrowband inversion sequence, inverting spins over a small range of rf amplitudes. R is a "read" pulse or pulse sequence. The FID signal in b(i) or b(ii) is subtracted from the FID in a. Contributions from transverse magnetization created by P are eliminated by dephasing during τ in b(i) or by phase cycling in b(ii), with $\phi = 0$ and $\phi = \pi$. When the pulses are applied with a surface coil, the remaining signal arises only from the localized spatial region in which P inverts spins and R excites signal.

(3′) Subtract the sum of the FIDs of step 2′ from the sum of the FIDS of step 1′. The phase cycling in step 2′ cancels the effects of residual transverse magnetization following P.

In principle, the two forms of NOBLE produce the same spatial localization. The choice is a matter of experimental convenience.

One effective narrowband inversion sequence is a sequence of 27 phase-shifted pulses, each with a nominal flip angle of π, which has been generated by iterative methods (*18*). Those methods will be described in a future publication. We use the term narrowband, in this case, to refer to selectivity with respect to the rf amplitude. In Fig. 2, we show a plot of the extent of population inversion as a function of B_1/B_1^0 for the 27-pulse sequence. B_1^0 is the nominal rf amplitude transverse to the static magnetic field. The nominal flip angles of pulses are defined with respect to B_1^0. B_1 is the actual transverse rf amplitude, a function of position. The extent of inversion is defined to be the negative of the final z component of a spin vector. The spin vector is assumed to be of unit length and to have an initial z component of 1. The narrowband property of the 27-pulse sequence is apparent in Fig. 2.

The inversion produced by the 27-pulse sequence is periodic in B_1/B_1^0, with a period of 2. Any sequence of π pulses will be periodic in this way. Thus, spins are inverted in regions of space where the rf amplitude is any odd multiple of B_1^0. This presents a problem for spatial localization. If B_1^0 is taken to be the rf amplitude at a region of interest at some distance from a surface coil, there will be regions closer to the coil where the rf amplitude is $3B_1^0$, $5B_1^0$, etc. These regions may contribute to the signal collected with NOBLE. If a gap between the surface coil and the sample is permitted, the problem is alleviated somewhat. However, it is still desirable to minimize at least the contributions from the $3B_1^0$ region.

One way to eliminate signal from the $3B_1^0$ region is to use a nominal $\pi/3$ pulse as the read pulse R. Then, at $3B_1^0$, R is in fact a π pulse and does not excite any

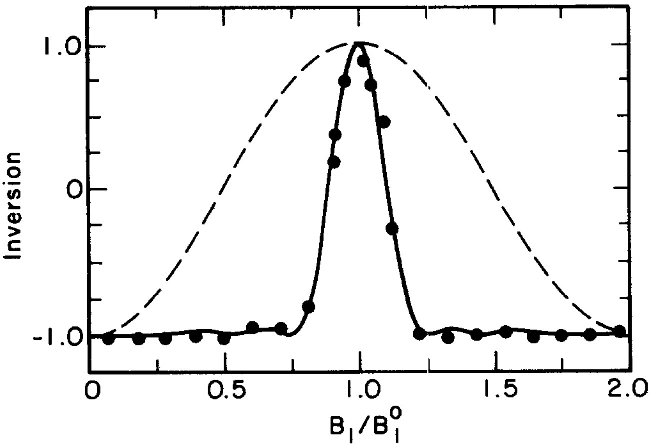

FIG. 2. Performance of a narrowband inversion sequence for use in NOBLE. The sequence consists of 27 rf pulses, each with a nominal flip angle of π, and with the following phases (degrees): 0, 120, 240, 120, 240, 0, 240, 0, 120, 120, 240, 0, 240, 0, 120, 0, 120, 240, 240, 0, 120, 0, 120, 240, 120, 240, 0. Simulations (solid line) and experimental measurements (dots) of the extent of spin population inversion as a function of the ratio of the rf amplitude B_1 to its nominal value B_1^0 are shown. For comparison, the simulated inversion performance of a single nominal π pulse is also shown (dashed line).

signal. The signal amplitude at B_1^0 is reduced by a factor of 0.866. In Fig. 3, we show a calculated plot of the signal amplitude as a function of B_1/B_1^0 resulting from either version of NOBLE, using the 27-pulse sequence of Fig. 2 for P and a nominal $\pi/3$ pulse for R. The signal amplitude is normalized to its value at $B_1 = B_1^0$. Note that the maximum signal in the $3B_1^0$ region is smaller than that at B_1^0 by a factor of 0.07.

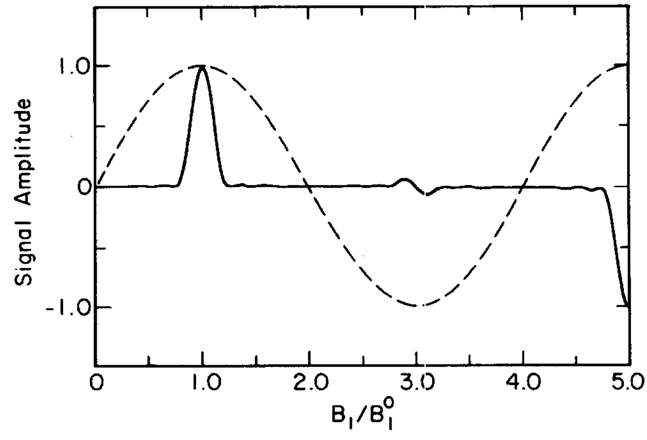

FIG. 3. Simulation of the signal resulting from NOBLE as a function of the ratio of the rf amplitude B_1 to its nominal value B_1^0 (solid line). The narrowband inversion sequence of Fig. 2 is used for P. A nominal $\pi/3$ pulse is used for R. For comparison, the signal amplitude resulting from a single nominal $\pi/2$ pulse is shown (dashed line). Signal amplitudes are normalized to their value at B_1^0. With surface coils, the narrowband excitation property of NOBLE produces spatial localization of signals.

Figure 3 applies to any surface coil geometry. It may be desirable to design a coil such that the size and shape of the B_1^0 region conforms to that of the interesting sample region. If the same coil is used for both the excitation and the detection of signals, then the observed signal amplitude is further weighted by a factor of B_1/B_1^0. This is because the intrinsic sensitivity at a given point in space is proportional to the transverse field amplitude that would be produced at that point by a unit current flowing in the detection coil (*25*).

Figure 3 is intended as an indication of the high degree of spatial localization that is possible with NOBLE. The qualitative features are independent of the specific pulse sequences used. Other choices for P, perhaps with a different periodicity, are possible. R may be a sequence of pulses, rather than a single pulse, with its own narrowband properties. It may also be profitable to combine NOBLE with shaping of the static magnetic field to further localize signals (*26*).

With both the surface coil and the sample held fixed, it is possible to move the region from which signals are detected in two equivalent ways. Either the rf power is varied while maintaining constant pulse lengths, or all pulse lengths in P and R are varied proportionally while maintaining a constant rf power. A series of NMR spectra from various spatial regions may thus be collected.

To conclude, we contrast NOBLE with the "depth pulse" method proposed by Bendall and Gordon (*10–12*). Both techniques rely on rf inhomogeneity to achieve spatial localization. The regions that contribute signal in the two techniques are therefore similar. However, in Bendall and Gordon's method, the sensitivity to rf amplitude arises from an extensive phase-cycling procedure. Many FIDs must be acquired before any spatial localization is achieved. In NOBLE, the spatial localization is inherent in the narrowband inversion sequence. Only two or four FIDs are required. In applications where the signal-to-noise ratio is sufficiently high after a small number of FIDs are accumulated, NOBLE is more efficient. In addition, NOBLE may be easier to implement due to the comparatively simple phase-cycling requirements.

Finally, we note that Shaka and Freeman have recently independently developed narrowband inversion sequences and have suggested their use in a spatial localization method (*17*).

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