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A Simple Design for a Double-Tunable Probe Head for Imaging and Spectroscopy at High Fields

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A double-tunable probe head based on the slotted tube resonator is described. Its performance at 2.35 T is comparable to that of single-tunable designs. The main advantages are a large tuning range, a probe volume that is not reduced by the second circuit, and a simple design.

INTRODUCTION

For optimum flexibility in the acquisition of NMR spectra from deeper lying tissue, *in vivo* spectroscopy requires coils generating homogeneous radiofrequency (rf) fields for different nuclei. For the construction of such double-tuned probe heads, one has to deal with several additional problems compared to coils operating only at a single frequency: (A) Generally, the performance is lowered for at least one of the frequencies; (B) the geometric arrangement of the two circuits often reduces the accessible probe volume; (C) the two interlaced circuits may require considerable skill in their construction. For work with infants in our 40-cm-bore system (*1*), points A and B were of particular importance, since we needed a design that did not reduce the already limited space and that gave an optimal signal-to-noise ratio.

To fulfill these requirements we built a slotted tube resonator which is capable of resonating at two frequencies and has a satisfactory spatial homogeneity of the rf field. While similar in performance to the original Alderman–Grant resonator (*2*), a large tuning range is maintained using capacitive tuning only, which simplifies tuning considerably. In this paper, the performance of the double-tuned probe head is compared to that of resonators of the same type containing only a single resonance circuit.

The slotted tube resonator was first presented as a structure capable of resonating at high frequencies in small vertical-bore systems (*3*). It was then modified to be used as a decoupler probe at high frequencies in situations where it is important to generate minimal electric fields to avoid sample heating, for example, during broadband decoupling (*2*). Subsequently, this probe design was also favored for *in vivo* applications, because low electric fields are generated and because the low self-inductance of these designs (*4*) enables operation at high frequencies and with large dimensions. A second circuit is not easily incorporated into the H-shape structure of the Alderman–

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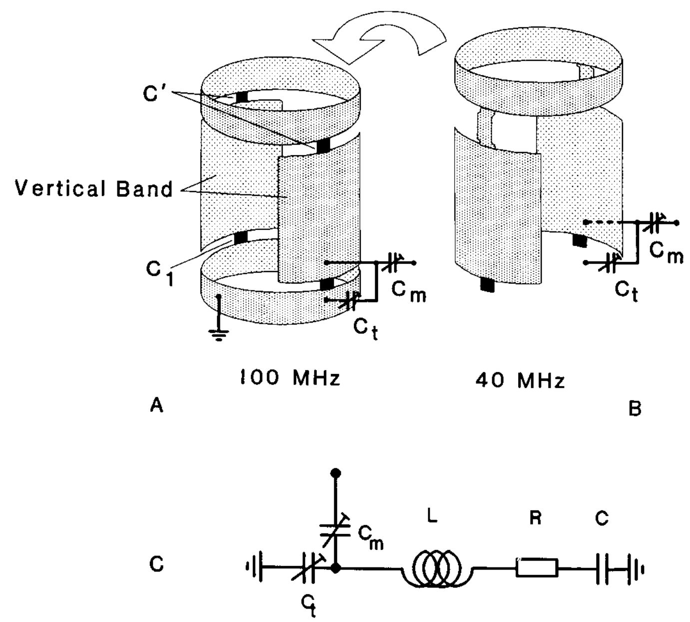

FIG. 1. Drawings of the resonating parts of the probe head discussed in the paper. (A) Circuit of the single-frequency probe head operating at 100 MHz. (B) Circuit for 40 MHz. Its combination with the 100-MHz circuit (arrow) is described in the text. (C) Equivalent circuit of A and B. C_t encloses the variable as well as the indicated fixed capacitance. The different resonance frequencies are obtained mainly by variation of the capacitance C (see text).

Grant resonator (*2*). For the construction of double-frequency probe heads based on this design that have so far been reported (*5*), the second circuit for the X-nucleus was placed inside the regular resonator, which resulted in a significantly reduced probe volume. Furthermore, for either single-circuit or double-circuit resonators using the original design (*2, 5*), the tuning range attainable with variable capacitors is very limited, and therefore additional mechanical adjustments have been made (*5*). Mechanical tuning requires not only skillful construction but also much patience when tuning the probe for different loading situations. Therefore, we have made a special effort to extend the tuning range in our construction.

DESIGN OF THE PROBE HEAD

The main structural features of the resonating part are shown in Fig. 1A. Two copper sheets cover an 80° arc each (*3*), and are capacitively connected to ground and via a ring to each other. This probe design is a variant of the slotted tube resonator by Alderman and Grant (*2*). Tuning and matching are performed capacitively. An equivalent circuit is drawn in Fig. 1C, where parasitic capacitances have been neglected, because we found this circuit to describe accurately enough the change in resonance frequency as a function of the various capacitors. In Fig. 1C, C can be defined as the equivalent capacitance in series to L. In other words, if the circuit contains two capacitances C' connecting the plates to the ring and a capacitance C_1 connecting that plate to ground, which is far from the feeding point (Fig. 1A), then

$$\frac{1}{C} = \frac{2}{C'} + \frac{1}{C_1}. \quad [1]$$

The circuit of Fig. 1C can be thought of as a combination of lumped elements, where the impedances are given by R, $i\omega L$, and $(i\omega C)^{-1}$, respectively. Two impedances Z_1 and Z_2 in series or parallel add up to the respective equivalent impedance according to the standard rules: $Z_{\text{series}} = Z_1 + Z_2$ and $Z_{\text{par}}^{-1} = Z_1^{-1} + Z_2^{-1}$. An explicit calculation then gives for the input impedance Z of the complete circuit

$$Z = \frac{Rm^2}{(m+x)^2 + y^2} + \frac{1}{i\omega C_t} * \frac{y^2 + x(m+x)}{(m+x)^2 + y^2} + \frac{1}{i\omega C_m} \quad [2]$$

where $m = C/C_t$, $x = 1 - \omega^2 LC$, and $y = \omega RC$. The circuit is tuned and matched to 50 ohms whenever the real part of the impedance is 50 ohms and the imaginary part is zero (*6*).

In the double-tuned probe head a second circuit rotated by 90° was added. The ring of the additional circuit was placed outside the ring of the first circuit (Fig. 1B, arrow). In principle, the resonance frequency could have been lowered by increasing the distributed capacitances C' and C_1 (Fig. 1A). However, to attain the resonance frequency of ^{31}P at 2.35 T (40.5 MHz), we would have needed quite large capacitances. Rather than increasing the distributed capacitance, we replaced the two capacitive connections between the two copper bands and the ring (C' in Fig. 1A) by a copper plate isolated with Teflon dielectric, and thereby increased the equivalent capacitance C (Eq. [1]). This resulted in a 30-MHz drop in resonance frequency. An additional drop of 30 MHz was achieved through an increase in the tuning capacitance (by increasing the capacitance parallel to the variable capacitor) and the remaining capacitance C_1. Table 1 gives an account of the geometry and the electrical details of the double-resonance probe head and the isolated circuits.

MATERIALS USED TO CONSTRUCT THE PROBE

The double-resonance probe head was constructed using home-built fiberglass cylinders; a copper net served as the grounded rf shield on the outer cylinder. The rings of both circuits, the crossings, and the inner cylinder were covered with 0.4-mm Teflon sheets. For the tuning and matching of the circuits we used four COMET CV05-45G/5 vacuum capacitors (Comet AG, Bern, Switzerland) with a range of 3–45 pF. The single circuits were mounted on a plexiglass structure with massive copper rf shielding on the outer cylinder. Here we used vacuum capacitors with a range of 3–30 pF (ITT Jennings CADC-30-15S). Fixed capacitors were purchased from various suppliers. The resonating parts of the circuits consisted of 0.2-mm-thick massive copper sheets (99.9% purity).

METHODS APPLIED TO DETERMINE PROBE CHARACTERISTICS

A first performance check of the resonance mode and measurement of the quality factors Q and tuning ranges was performed using a sweep generator (Wavetek, Kon-

TABLE 1

Geometry and Electrical Characteristics of the Probe Head in Fig. 1[a]

	Double-tunable probe head		Single-tunable probe head	
	^{1}H	^{31}P	^{1}H	^{31}P
Support material	Fiberglass		Acrylic glass	
Shielding ground	Copper net		Copper sheet	
Inner diameter (mm)	240		240	
Outer diameter (mm)	325		350	
Ring thickness (mm)	15		25	
Plate length (mm)	260		280	
C_1 (pF)	32	90	30	112
C' (pF)	32	—	40	—
C_t (pF)	13–55	73–115	23–50	103–130
Tuning range (MHz)	15	3.5	7	2
Estimated inductance (nH)	320	350	240	280
Q, empty	400	500	580	700
Q, loaded[b]	110	220	120	220
180° pulse[c] (empty) (μs)	260	440	150	320
Homogeneity[d]				
h (mm)	170	250	150	250
a (mm)	80	>100[e]	100	>100[e]
b (mm)	170	>100[e]	200	>100[e]

[a] The NMR performance of the double-tunable probe head was compared with that of a resonator equipped with one resonant circuit only (Fig. 1A), which was previously used for routine imaging and then modified to resonate at 40.5 MHz.

[b] The sample consisted of a bottle filled with a physiologic sodium chloride solution doped with $CuSO_4$, which mimicked the load of an adult leg or a large head.

[c] Measured at 1 kW of transmitter power with a negligible load.

[d] Given are the dimensions of an elliptical cylinder of height h, and with the principal axes a (in direction of the polarization) and b (between plates). In this volume, the spatial variation of B_1 is less than 10% of the on-axis value.

[e] Measurements remote from the magnet center were impaired by the effect of limited gradient linearity (eddy currents) and magnet homogeneity on gradient-recalled images.

tron, Zürich, Switzerland). All NMR experiments were carried out on a 2.35-T superconducting magnet (Bruker/Spectrospin, Fällanden, Switzerland) with a horizontal room-temperature bore of 40 cm. The instrument is installed in clinical surroundings (*1*).

The sample for the determination of the 180° pulsewidths for ^{1}H in the single-circuit probe was a small glass bottle filled with 1 ml of distilled water. A bottle filled with approximately 30 ml of an aqueous sodium phosphate solution was used for the ^{31}P single-circuit probe and for both frequencies of the double-tuned probe head.

An obvious but tedious way to measure the rf homogeneity would be to determine the 180° pulsewidths of a small sample moved around systematically to cover the whole interior of the probe head. We chose a different, more efficient way that proved to be equivalent. The pulse scheme used to assess the spatial homogeneity of the rf field for protons (100 MHz) consisted of a simple spin-echo sequence in the presence of a gradient in the axial direction of a cylindrical sample. This resulted in a projection of the phantom, which was a circular glass cylinder of 2 cm diameter and 22 cm length filled with a 200 mM potassium phosphate solution. The sample was centered either vertically or along z in the magnet's isocenter. This had the advantage that the experimental setup did not have to be changed when the probe head was moved around the sample.

The rectangular pulses corresponded to a flip angle of the order of 20° (15–25 μs at 1 kW of power). Transverse magnetization excited by a rectangular pulse of duration τ is proportional to $\sin(\gamma B_1 \tau)$ and the amplitude of a spin echo recalled by a second, identical pulse is proportional to $\sin^2(\gamma B_1 \tau/2)$ (*7*). The signal acquisition is proportional to B_1. Thus, an echo generated by two identical rectangular pulses of duration τ is proportional to $B_1 \sin(\gamma B_1 \tau) \sin^2(\gamma B_1 \tau/2)$. With the approximation that $\sin x \approx x$ for small x, the projection obtained in our experiment is thus proportional to B_1^4, and relative rf field strengths were calculated by taking the fourth root of the projection. Because of the low sensitivity of ^{31}P, we used a gradient-recalled echo with a low flip-angle pulse (τ = 15–50 μs at 1 kW) to measure the rf field homogeneity. The signal is then proportional to $B_1 \sin(\gamma B_1 \tau)$, and in the case of small flip angles the square root of the projection yields the relative variation of the rf field B_1. Since in our instrument the rf homogeneity of the probe head extended beyond the homogeneity of the static field B_0 and beyond the linearity range of the gradients (eddy currents), we measured in several steps along the z direction by changing the probe head position along its axis. In the transverse direction the measurements were restricted to a cylindrical area of 10-cm diameter centered about the axis of the probe head.

For both nuclei, projections in the transverse direction were recorded by rotating the probe head around the vertically positioned, cylindrical phantom in 45° steps and translating it in the z direction in 5-cm steps.

RESULTS: COMPARISON WITH SINGLE-CIRCUIT PROBE HEADS

To judge the performance of the double-tuned circuit we compared it to a single-frequency probe head built with the same design (Fig. 1A) which we had used as a routine imaging probe head for 2 years. After measuring its performance at 100 MHz, we modified the single-circuit probe head to resonate at 40 MHz. The results of this comparison are summarized in Table 1. Note the large tuning ranges, especially at 100 MHz, which in principle allow the ^1H–^{31}P double-tuned probe head to be tuned also to the resonance frequency of ^{19}F. The differences between the tuning ranges of the single-circuit and double-frequency probe heads are due mainly to the different types of vacuum capacitors used. From the tuning range and the values of the capacitors we can deduce the inductance of the respective circuit with Eq. [2], when losses R and stray capacitance are not taken into consideration. The resulting values shown in Table 1 are in good agreement with those of similar structures presented earlier (*4*). The electrical isolation of the two feeding points was determined by measuring the power picked up in one circuit when pulsing with 1 kW power in the other circuit. The 40-MHz transmitter signal is suppressed by 41 dB in the 100 MHz circuit, and the 100 MHz signal is attenuated by 21 dB in the 40 MHz circuit. Tuning and matching are independent for both circuits with the sole exception that C_m at 40 MHz does have a slight influence on the matching condition of the 100-MHz circuit.

At the bottom of Table 1 the NMR characteristics of the probe heads are given. Generally it seems that transverse homogeneity is worst in the direction of the polarization of the rf field and best in the direction of the emitting plates. To quantify the spatial extensions of the area of good rf homogeneity, we determined the dimensions of elliptical cylinders in which B_1 varies by less than 10% of the on-axis value in the transverse planes. Along the cylinder axis the B_1 variations are less than 10%. For the single-circuit ^1H probe head the elliptical cylinder is of height 15 cm, with axes of 10 and 20 cm. For ^1H in the double-frequency probe head, the cylinder is 17 cm in height, with axes of 8 and 17 cm, indicating that the transverse homogeneity in the direction of the polarization of the rf field falls off more rapidly than in the single circuit.

For phosphorus, the rf homogeneity measurements were impaired outside of a sphere of 10 cm in diameter in the magnet isocenter (cf. above). It is therefore difficult to judge the performance off-axis. In the longitudinal direction we could not find major differences in rf homogeneity at 40 MHz between the two probe heads.

Under *in vivo* conditions, the quality of the proton images in terms of signal-to-noise ratio was found to be similar to that of the single-circuit resonator which was used for imaging in over 150 examinations (*1*) and the double-tuned probe head. We actually replaced the standard imaging probe head by the double-frequency resonator for routine magnetic resonance imaging and have by now used it for more than a year in over 100 examinations. We also used it for combined imaging and spectroscopy experiments in phantoms and in a few patients. Because rf homogeneity is best illustrated by cross sections and since the quality of the volume selective spectroscopy results is still limited by the gradient switching characteristics of our magnetic resonance system, we compare images obtained by the two different circuits of the double-tuned probe head (Fig. 2). Figure 2A is an example of a T_2-weighted sagittal section through the head of a 4-month-old child, which shows an rf homogeneity that satisfies our clinical demands. For phosphorus, excellent longitudinal homogeneity is achieved, as documented by the sagittal ^{31}P spin-echo image (Fig. 2B) of our phantom.

DISCUSSION

This paper describes a double-tuned probe head which is closely related to the Alderman–Grant resonator (*2*). However, because the tuning range of the modified coil is as large as 15 MHz, it is much simpler to match and tune than the original Alderman–Grant device, where additional screws are to be adjusted for the mechanical tuning, and the tuning range is nevertheless still limited to a few megahertz (*5*). With the design used here, additional multinuclear applications, such as combined acquisition of fluorine and phosphorus after recording ^1H data, are possible. Another advantage of the presently described probe head is that in contrast to other schemes, the probe volume remains unaltered by the introduction of a second circuit. This is of importance in situations in which the accessible probe volume has to be used

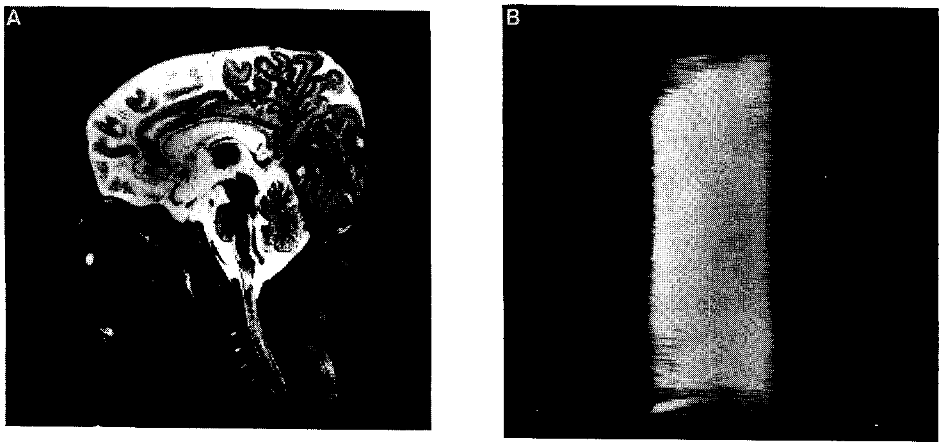

FIG. 2. (A) Sagittal T_2-weighted section (SE 3000/120) through the head of a 4-month-old child with brain atrophy. (B) Sagittal ^{31}P (SE 3000/22) image of a bottle (22 cm long, 8 cm in diameter) filled to 40% of the full volume with a potassium phosphate solution. The bottle lies along the magnet axis. Toward the ends of the phantom the limited magnet homogeneity and gradient linearity distort the image quality. Both images were recorded using a single spin-echo technique (*1*), with slice thicknesses of 5 mm for ^1H and 40 mm for ^{31}P. In both cases the field of view was 20 cm.

economically, as in our setup with a bore size of only 40 cm. Finally, the design in Fig. 1 is simple to construct. For example, the presently described resonator was built even though we had only limited access to electronic equipment and infrastructure. Overall, we feel that the probe head in Fig. 1 has distinct advantages when its performance, probe volume, and simple construction are considered.

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