JOURNAL OF MAGNETIC RESONANCE IMAGING 10:216–219 (1999)

Technical Note

Electron Spin Resonance (ESR) Probe for Interventional MRI Instrument Localization

Gösta J. Ehnholm, DSc, [2]* Erkki T. Vahala, MSc, [1] Jaakko Kinnunen, MD, [1] Jukka E. Nieminen, MSc, [2] C.-G. M. Standertskjöld-Nordenstam, MD, [1] and Mikko A. Uusitalo, DSc, [2]

This article presents a miniaturized electron spin resonance (ESR) probe for deducing the position of a surgical instrument on an MR image. The ESR probe constructed was small enough to fit inside a 14-G biopsy needle sheath, and position information of the sheath could be acquired using a simple gradient sequence. The position accuracy was estimated from needle trajectories as inferred from the needle artifact, the actual physical trajectory, and measured coordinates. The probe was able to track the tip of a biopsy needle quickly (10 samples/sec) and precisely with accuracy better than ±2 mm. J. Magn. Reson. Imaging 1999;10:216–219. © **1999 Wiley-Liss, Inc.**

Index terms: interventional MRI; ESR; MRI guided procedures

GUIDANCE SYSTEMS in MRI are often classified as active or passive: The former use non-magnetic trackers, eg, optical (1,2) or ultrasonic (3,4) devices, the latter relying upon deliberately caused artifacts or local signal intensity changes in acquired MR images, eg, effects produced by titanium needles (5) or catheters (6).

Active devices track their position in real time. The absolute position accuracy can be good, but the coordinates obtained have to be matched with those of the MR image by careful calibration. This is tedious and, due to image distortions caused, eg, by gradient nonlinearity, it cannot be very precise.

Passive systems are inexpensive and relatively simple to use. The are not hampered by image distortion. However, position accuracy and acquisition speed are limited, for example by signal-to-noise ratio, and depend on used imaging sequence.

The electron spin resonance (ESR) probe is an alternative that, like real-time NMR needle tracking (7), lies somewhere between the categories mentioned. In both cases a probe measures the local magnetic field produced by the gradient coils. In the former, an ESR is used, in the latter, a nuclear magnetic resonance, usually in a water sample. With a suitable gradient sequence the output data can be used to calculate the position of the probe. As a consequence the positions determined are influenced by the nonidealities of the gradient coils in much the same way as the actual MR images, which means that the corresponding errors are largely compensated. The advantage of the ESR over the NMR method is that a more compact probe can be constructed because the resonating sample can be made smaller. Another advantage is that the ESR frequency is higher and the relaxation times faster, making the probe faster to use.

THEORY

Field measurements of the ESR probe are based on the ESR phenomenon, which is present in certain substances, eg, radical-ion TCNQ (N-methylpyridinium), which contain unpaired paramagnetic electrons. These resonate in a magnetic field with a frequency that is proportional to the field strength and 658 times the proton resonant frequency. The effect is seen in a strong increase in the susceptibility of the substance as the frequency of the measuring signal on a sample is swept through the resonance. If the sample is inside a suitably tuned microwave resonator, it is possible to deduce the magnetic field: the drastic susceptibility change at resonance is reflected as a change in both the resonant frequency and the electrical losses of the resonator. It is relatively straightforward to build a highly sensitive field-measuring device by measuring the properties of the resonator.

One method is to feed an input signal to the resonator and use the amount of reflected signal as an indicator of whether the sample is resonating. From this a feedback signal can be derived, which adjusts the input signal frequency so that the resonance condition becomes fulfilled all the time. The input signal frequency then tracks the resonance of the sample and becomes proportional to the magnetic field acting on it. This provides the needed field strength data (8).

The position encoding can be achieved with several different gradient sequences. Figure 1 illustrates one of the basic sequences.

Three orthogonal gradients are used to produce bipolar pulses one at a time. For simplicity, let us concen-

[1]Department of Radiology, Helsinki University Central Hospital, Meilahti Clinics, 00029 Helsinki, Finland.

[2]Picker Nordstar, Inc., 01510 Vantaa, Finland.

*Address reprint requests to: G.J.E., Picker Nordstar, Inc., Äyritie 4, 01510 Vantaa, Finland.

Received April 27, 1999; Accepted April 29, 1999.

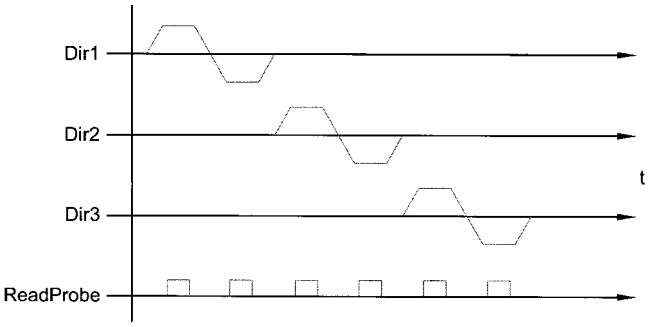

Figure 1. Position encoding gradient sequence for ESR magnetometer.

trate on a single gradient: the "ReadProbe" signal corresponds to sampling the magnetic field value with the ESR probe. To compensate for possible unwanted field fluctuations, such as temperature drift, sampling is performed during both positive and negative gradient currents. The difference of the field values is taken, which leaves a result that is insensitive to slow field fluctuations and depends only on gradient field. As the strength of the gradient pulse is known, the position of the ESR probe along the gradient direction can be calculated.

MATERIALS AND METHODS

The guidance system presented here is based on the 0.23 T Outlook MRI scanner (Picker International). The imager was used to assess the probe in a practical environment by imaging a phantom and comparing the image coordinates with the coordinates produced by the ESR probe. The probe itself was fitted inside a biopsy needle.

For a biopsy needle it is favorable to build the device using a coaxial type of a resonator. In this case the resonator was made of a 10-cm piece of EZ-47Cu semirigid coaxial cable (Huber+Suhner, Switzerland), and placed inside an MRI-compatible 14-G sheath (Somatex GmbH, Germany). A sample of the paramagnetic substance TCNQ (Nycomed Innovation, Sweden), having an approximate size of 0.5 × 0.5 × 0.5 mm, was placed close to the end of the coaxial resonator, where the center wire is connected to the outer conductor, as shown in Fig. 2. Due to its unknown tissue compatibility, the substance is best protected from the environment by applying a drop of epoxy onto the tip of the cable.

The magnetic field of the microwave resonator is strong at the chosen sample position. Hence the magnetic coupling between the sample and the resonator is also strong. This makes the microwave power dissipation in the sample, which is large when the magnetic resonance condition is fulfilled, become a significant part of the overall losses in the resonator. A quality factor, or Q-value, characterizes the losses of a resonator. It can be monitored by feeding constant power to the resonator and measuring produced energy content. Alternatively, one can measure the reflected power when a signal generator is weakly coupled to the resonator. The latter method results in a particularly simple arrangement containing one cable linking the resonator to the control electronics, where the incident and reflected power are separated (cf. Fig. 2).

The ESR control electronics utilized a frequency locking technique with field modulation (9) at an intermediate frequency (IF) acting on the ESR sample, ie, the reflected 6.45 GHz super high frequency (SHF) microwave signal from the resonator is amplitude modulated by a varying magnetic field acting on the ESR sample at the IF frequency of 80 kHz. The field modulation is arranged with a separate coil. The advantage of the field modulation in the system is that the measurement becomes insensitive to variations in the signal gain. Control electronics demodulate the reflected signal and use it as feedback for a microwave voltage-controlled oscillator (VCO), which provides the incident signal. A read-out signal is formed from the VCO output by mixing it down to a lower frequency and digitizing the result in a frequency counter. The read-out is integrated digitally for 8 msec, to filter out noise. The chosen integration time makes it possible to read 30 coordinates during 1 second, which is enough for real-time applications.

Error Sources in the Probe

If errors arising from non-ideal MRI magnetic fields are not taken into account, the position error in probe coordinates is mainly limited by noise in ESR control electronics, especially phase noise of the oscillator responsible for producing the SHF frequency needed for field locking. This noise has been measured and corresponds to an uncertainty of ~1 kHz in the frequency, which further corresponds to field noise of 50 nT_{rms}.

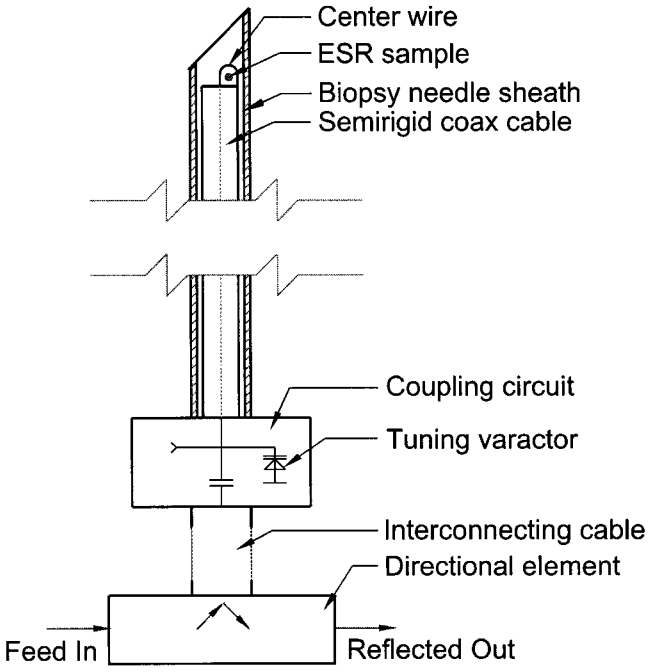

Figure 2. Microwave parts of an ESR probe, adapted for use with biopsy needles.

Random fluctuations in coordinates should preferably be under ±0.5 mm, ie, subvoxel in normal imaging sequences. This sets a lower limit to the encoding gradient: its strength should be high enough to make the noise correspond to less than 0.5 mm. This gives very modest values, on the order of 250 μT/m.

RESULTS

The functionality of the ESR probe was demonstrated in two ways:

1. By imaging markers and comparing the respective positions given by the probe.
2. By inserting the probe into a phantom and then tracing it in real time on the regularly updated MR images of the phantom.

An identical imaging sequence was used in both cases, to facilitate the comparison of accuracy.

Marker Study

Two circular MRI markers with a hole in the middle, model-3002 (Elekta, Sweden), were glued together. The tip of the ESR probe was centered into the tubular hole formed and the contraption placed into the scanner.

Using the coordinates from the ESR probe, images of 1 × 1 mm resolution in transversal, sagittal, and coronal directions were taken. The positional error was determined as the difference between sample coordinates produced by the probe and the center of the MRI markers measured from the images. Accuracy was examined at 24 evenly spaced positions inside a sphere with a diameter of 300 mm.

The gyromagnetic ratio of TCNQ, which gives the dependence of resonance frequency on magnetic field, was not known beforehand with the necessary accuracy. Also, the local magnetic field acting on the ESR sample depends on susceptibility of the environment. Therefore the resulting error first contained a linear term of approx. 3%, varying with the distance from the imaging volume center. The term was removed by a slight adjustment of the gyromagnetic ratio. After this, the remaining root-mean-squared sum of offsets in all three directions showed almost a random behavior (Fig. 3). The magnitude stayed below 2 mm inside the examined volume. Much, probably more than half, of this error is caused by the fact that the pixel size is 1 mm, limiting the accuracy for reading out image coordinates. Note that no calibration was needed to make the origin of the probe coordinates coincide with that of the image.

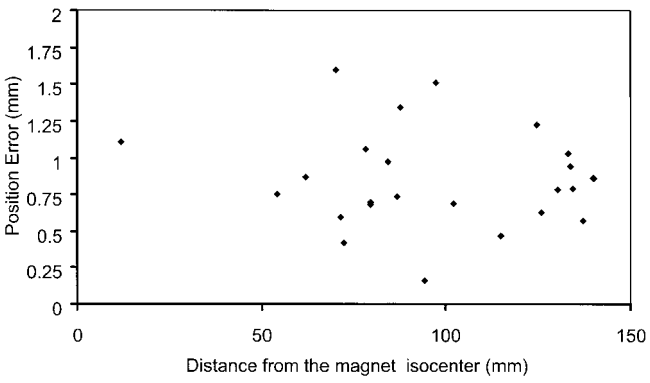

Figure 3. Position error as a function of the distance from the magnet isocenter.

Phantom Study

The objective of this study was to simulate a procedure by taking a "preoperative" image and superimposing the position of the ESR probe on it. The ESR probe positions were determined using the same value for the gyromagnetic ratio as in the marker study.

The position error, estimated from four cod liver oil capsules (Lysi, Iceland), was within 2 pixels, or ±2 mm, for the sequence used. A "preoperational" image was taken from a kiwi fruit. A biopsy sheath containing an ESR probe was inserted into the fruit along the image plane and the progress of the probe tip traced, ie, as the tip progressed its coordinates were computed. The corresponding orthogonal projection point on the image plane was determined and superposed on the image. The progressing points formed a trace for the inserted probe. Additional images were taken en route to compare the superimposed data with the needle artifact seen in the image (Fig. 4). The 14-G biopsy sheath was perpendicular to the B_0 field and thus caused a large artifact. The sequence parameters were as follows: FE 40/12 msec, field of view 256 × 256, flip angle 30°, 10 mm coronal slice, and imaging time 10 seconds.

Afterwards the fruit was sectioned and photographed with the needle still in place. The photograph was fitted on the MR image using shape lines as a guide. The distortion of the MR image was presumed to be insignificant—the small dimensions (< 100 mm) of the phantom in the middle of the homogeneous volume yield an error less than 1 mm at the edges of the image. This was also affirmed by the close fit of the image and the photograph (Fig. 5). The light background marks the rectangular photograph placed onto the MR image having darker, noisy background. Then the measured trace was plotted on the photograph, shown as an almost continuous trace of white dots. The needle on the background helps to visualize the position error.

The direction of the needle changed slightly at the beginning of the insertion, which explains the discrepancy between the trace and the needle at the other end. Also visible in the trace is a quick lateral movement of the needle. It shows the location where the needle tip penetrated the thick peel of the fruit. The position error was confirmed to be within ±2 mm at six fixed and equidistant positions. The experiment shows that the probe is capable of providing accurate, uninterrupted position information even when the needle bends.

DISCUSSION

The ESR probe functioned according to expectations: The coordinate acquisition speed (10 samples/sec) was adequate for instant feedback and can be further increased, if so needed, by increasing the gradient strength in the positioning sequence. Increased eddy currents

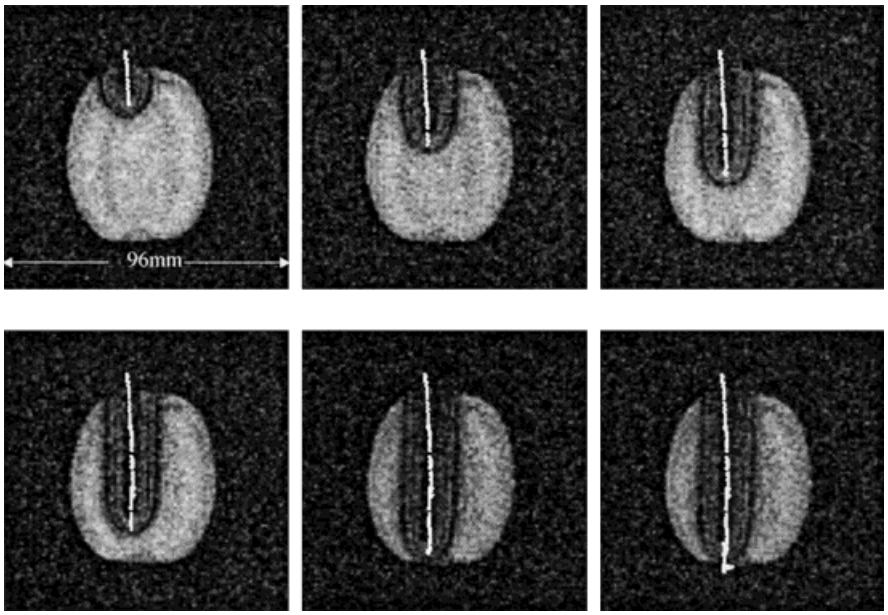

Figure 4. Image sequence acquired from a kiwi fruit, showing ESR probe trace.

and the dynamic range of the ESR control electronics ultimately limit the speed to 20 samples/sec with the current system.

The accuracy was better than ±2 mm for small objects (region of interest diameter < ~100 mm). Inaccuracies were mainly due to calibration difficulties (large voxel size) of the prototype system and can be made smaller, eg, using dedicated coils for enhanced marker visibility and smaller field of view to pixel ratio. A titanium sheath with smaller artifact, or the further miniaturization through the use of 18-G needles, can reduce the large artifact now present in the images.

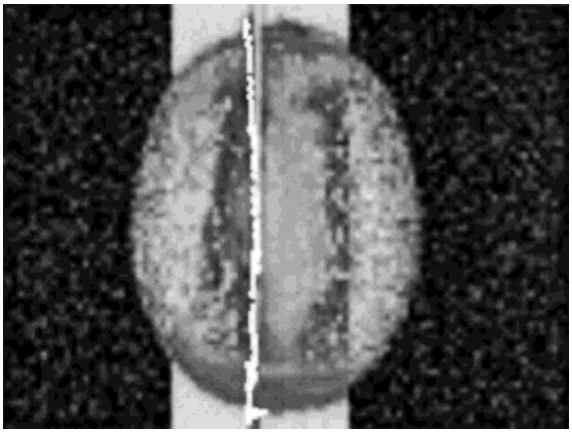

Figure 5. Photograph from the sectioned kiwi combined with the MR image and ESR probe trace.

In conclusion, the probe demonstrated the practicability of using ESR for positioning biopsy needles in MRI. It has the same advantages as small NMR fiducial coils used for that purpose, correcting for gradient coil nonlinearity and other similar effects. In addition, it has inherently better signal-to-noise ratio for the same sample size, so that the probe can be made smaller and faster and can be used at lower fields. The sample material is a solid with good long-term stability.

REFERENCES

1. Rohling R, Munger P, Hollerbach JM, Peter T. Comparison of relative accuracy between a mechanical and an optical position tracker for image-guided neurosurgery. J Image Guided Surg 1995;1:30–34.
2. Silverman SG, Collick BD, Figueira MR, et al. Interactive MR-guided biopsy in an open-configuration MR imaging system. Radiology 1995;197:175–181.
3. Horstmann GA, Reinhardt HF. Micro-stereometry: a frameless computerized navigating system for open microsurgery. Comput Med Imaging Graphics 1994;18:229–233.
4. deSouza NM, Coutts GA, Puni RK, Young IR. Magnetic resonance imaging guided breast biopsy using a frameless stereotactic technique. Clin Radiol 1996;51:425–428.
5. Lewin JS, Duerk JL, Jain VR, et al. Needle localization in MR-guided biopsy and aspiration: effects of field strength, sequence design, and magnetic field orientation. AJR 1996;166:1337–1345.
6. Bakker CJ, Hoogeveen RM, Weber J, et al. Visualization of dedicated catheters using fast scanning techniques with potential for MR-guided vascular interventions. Magn Reson Med 1996;36:816–820.
7. Steiner P, Erhart P, Heske N, et al. Active biplanar MR tracking for biopsies in humans. AJR 1997;169;735–738.
8. Pat. U.S. 5,488,950. Stabilizer for MRI system. Picker Nordstar, Inc. Finland (Ehnholm, G.). Appl. 212,426 March 14, 1994.
9. Duret D, Beranger M, Moussavi M. A new ultra low-field ESR spectrometer. Rev Sci Instrum 1991;62:685–694.