Improved depth sensitivity by separation of excitation and detection coils

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A laparoscopic probe for magnetic sentinel node biopsy has been developed. Superparamagnetic iron oxide nanoparticles (SPIONs) are used as a tracer. They are selectively detected by Differential Magnetometry (DiffMag). Excitation and detection coils are separated. To make this possible, we developed active compensation, which removes influence of the excitation field. Separation of coils leads to improved depth sensitivity, from 20 mm with our handheld probe to 80 mm with our novel laparoscopic probe. As stated by Biot-Savart law, we win a factor distance to the third power by separating the excitation and detection part of the system.

I. Introduction

A novel laparoscopic probe for magnetic sentinel node biopsy has been developed, as shown in Fig. 1. Sentinel node biopsy is a procedure to determine if a tumor has metastasized via the lymphatic system [1], enabling personalized patient care. To find lymph nodes that have the highest chance on containing metastases – sentinel nodes – we make use of superparamagnetic iron oxide nanoparticles (SPIONs) as a tracer.

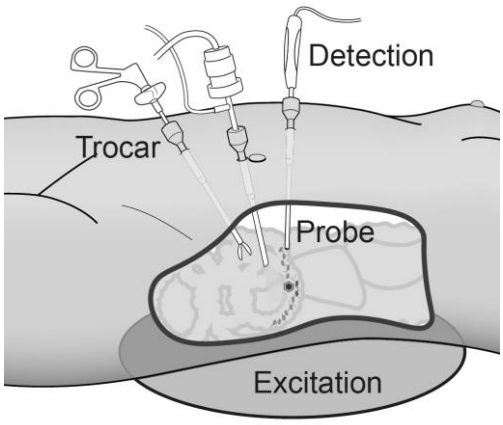

Figure 1: *Novel laparoscopic probe for magnetic sentinel node biopsy. Excitation and detection part of the system are separated to improve depth sensitivity.*

To selectively detect SPIONs in the diamagnetic human body we make use of Differential Magnetometry (DiffMag). DiffMag utilizes nonlinear properties of SPIONs, similar to MPI and MPS. The main differences are that we use a smaller AC amplitude (± 1 mT) and measure in the time domain instead of harmonics spectra. In DiffMag, the excitation field consists of two parts: a continuous AC field and DC offsets. The total excitation sequence consists of four parts: no DC offset ($u_{0,1}$), a positive DC offset (u_+), no DC offset ($u_{0,2}$) and a negative DC offset (u_-). Due to nonlinearity of SPIONs, the amplitude of the detected signal is lower when a positive or negative DC offset is applied. The difference in amplitude between blocks with and without DC offsets is defined as DiffMag counts:

$$DiffMag\ counts = \frac{1}{2}\left[\left(u_{0,1} - u_+\right) + \left(u_{0,2} - u_-\right)\right]$$

Similar to MPI and MPS, DiffMag makes use of excitation and detection coils. A handheld probe was developed that contains both excitation and detection coils for use in open surgery [2]. However, in laparoscopic surgery, the diameter of the probe is restricted by the use of standard trocars. The depth sensitivity of a coil is determined by the diameter of the coil, according to Biot-Savart law. As a result, making the handheld probe smaller would result in inadequate depth sensitivity, making it impossible to find sentinel nodes in laparoscopic surgery.

II. Material and Methods

II.I. Setup

The problem of limited depth sensitivity can be solved by separation of the excitation and detection part of the system. The excitation coils will be large and placed underneath the patient, as shown in Fig. 1. The detection coils can be small enough to fit through standard laparoscopic trocars (12 mm).

The main challenge after separating excitation and detection coils is movement of the detection coils with respect to the excitation coils, leading to a changing mutual inductance. The detector signal will be obscured by the changing excitation field, making it impossible to detect the tiny magnetic signature of SPIONs.

To solve this problem, we developed active compensation. Compensation coils are used to couple in extra field. This field is actively adjusted to match imbalance of the probe.

This imbalance of the probe is caused both by the excitation field and by materials with a linear magnetic susceptibility in the mT field range, such as tissue and surgical steel. Active compensation is only possible because we make use of DiffMag. Due to the extra field, the amplitude of the measured signal changes. However, the difference in amplitude – DiffMag counts – remain exactly the same.

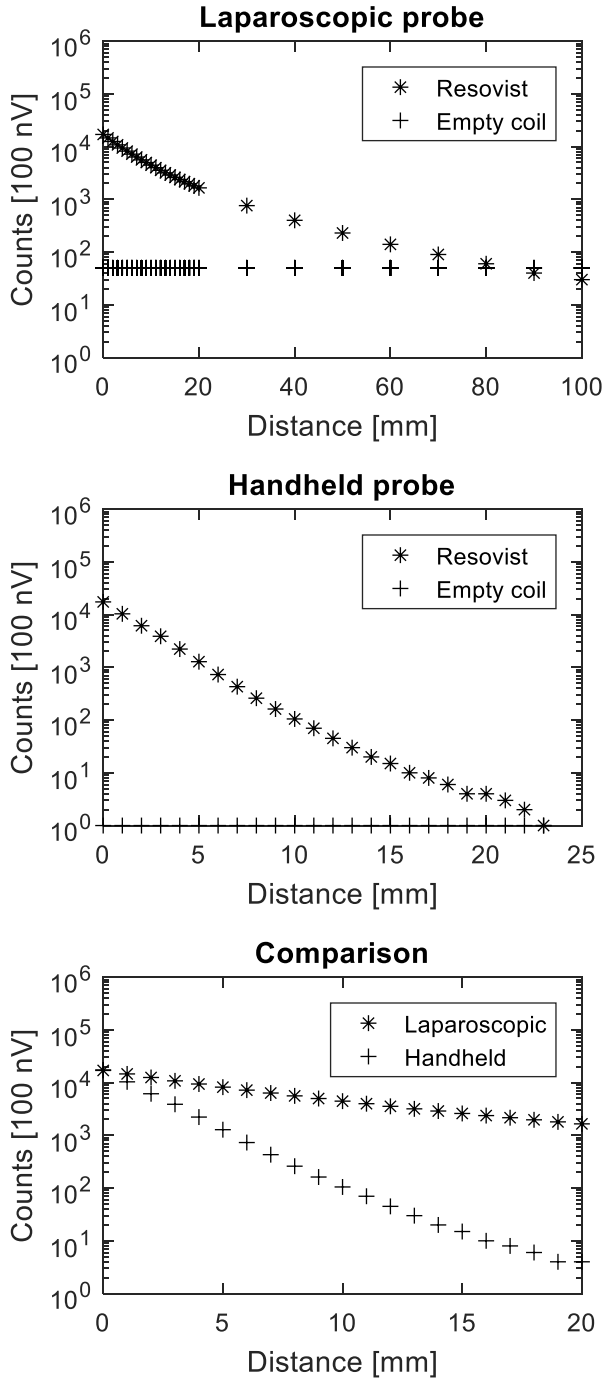

Figure 2: *Measurement results for our laparoscopic and handheld probe at various distances to the probe.*

II.II. Material

A Resovist® (Bayer Schering Pharma GmbH) sample of ± 1.5 mL containing ± 45 mg Fe was used in all measurements.

II.III. Measurements

The sample was measured at various distances to the probe with our laparoscopic probe and our handheld probe. For the laparoscopic probe, with separated excitation and detection coils, the sample was placed at a set location in the excitation field (at the central axis through the coil, 3 cm above excitation coil surface). The probe containing the detection coils was first positioned directly on top of the sample. Next, a robotic arm (Meca500, Mecademic) was used to move the probe upwards. For the first 20 mm this was done in steps of 1 mm, and after 20 mm in steps of 10 mm to a total distance of 100 mm. For the handheld probe, the probe was placed on top of the sample and then moved upwards in steps of 1 mm to a total distance of 20 mm.

III. Results

Measurement results are shown in Fig. 2. It is shown that SPIONs can be measured 20 mm deep with our handheld probe and 80 mm deep with our laparoscopic probe.

IV. Discussion

Increase in depth sensitivity from 20 to 80 mm is a result of separation of the excitation and detection part of the system. Decrease of a magnetic field over distance is described by Biot-Savart law. How rapid the field decreases is influenced by both the diameter of the coils and the distance to the sample. Biot-Savart law states that the magnetic field created by a circular coil decreases with distance to the third power. In the handheld probe, measuring nodes that lie deeper in tissue means an increased distance to the excitation coils as well as to the detection coils. Consequently, the measured signal decreases with distance to the sixth power. In our novel laparoscopic probe, the excitation and detection part are separated. Therefore, measuring deeper nodes only leads to increased distance to the detection coils, so the measured signal decreases with distance to the third power.

V. Conclusions

Our solution of separating excitation and detection coils leads to a fundamentally better depth sensitivity. As stated by Biot-Savart law we win a factor distance to the third power when the diameter of the probe remains constant.

ACKNOWLEDGEMENTS

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REFERENCES

[1] A. E. Giuliano and A. Gangi, “Sentinel node biopsy and improved patient care,” Breast J., vol. 21, no. 1, 2015.

[2] S. Waanders, M. Visscher, R. R. Wildeboer, T. O. B. Oderkerk, H. J. G. Krooshoop, and B. Ten Haken, “A handheld SPIO-based sentinel lymph node mapping device using differential magnetometry.,” Phys. Med. Biol., vol. 61, no. 22, pp. 8120–8134, Nov. 2016.