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A portable single-sided magnetic particle imaging concept using amplitude modulation for breast conserving surgery

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Abstract

In breast-conserving surgery (BCS), complete removal of breast cancers and minimal expulsion of normal cells are very important. Since surgery is a burdensome treatment for the patient, the surgical procedures should be minimally invasive while ensuring the maximum degree of completion. Before and after surgery, the location of the tumor and the presence of residual tumor can be checked through examination outside the operating room. However, if residual tumors are identified in the postoperative examination, reoperation or additional chemotherapy is required. Therefore, in order to improve the degree of completion during surgery, a portable single-sided magnetic particle imaging that can be used inside the operating room is presented. Using these devices, the presence of residual tumor can be examined in real-time before suturing the affected area. Furthermore, this article proposes how detecting the exact location will improve the completion of the initial surgery.

I. Introduction

Since Magnetic Particle Imaging (MPI) was first proposed, research in this field has been conducted in many directions. Various methods for performing MPI have been developed. One such method is the single-sided MPI using a Field Free Line (FFL) [1]. A miniaturized device that utilizes a Field Free point (FFP) to find sentinel lymph nodes in breast cancer has also been proposed [2]. Surgical interventions for breast cancer are moving towards non-invasive and minimally invasive techniques. The majority of patients who have had a mastectomy consider it as losing attractiveness and see themselves as being disabled [3]. On the other hand, the fear of recurrence is increased in patients who choose breast-conserving surgery despite there being no significant effect on the survival rate [4]. As a result, they experience a long process of psychological stress before, during, and even after treatment.

Most of the current medical imaging devices (CT, MRI, etc.) used to examine breast cancer are large, closed and fixed type. Therefore, they are not suitable for use inside the operating room. Accordingly, examinations are performed outside the operating room, and surgery plans are established based on the data. Due to this limitation, it is difficult to provide immediate feedback even if there is a problem with the operation. Therefore, to improve the completeness of the surgery, real-time devices have been suggested that can be used inside the operating room [5,6,7,8]. By utilizing the real-time device in the operating room the fear and anxiety that tumors are not completely removed through the process shown in Figure 1 can be further reduced.

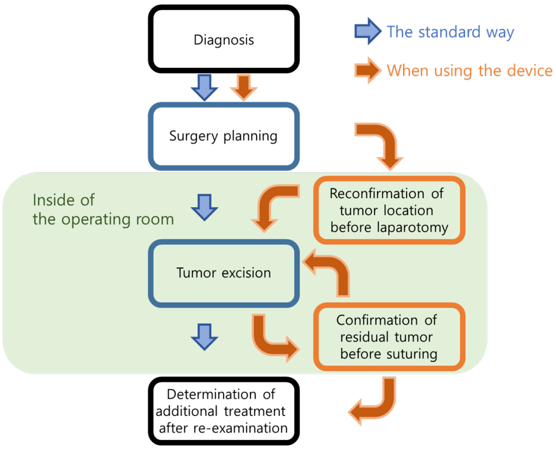

Figure 1: The existing treatment method (left) and the changes in the treatment process that will occur when the device is introduced into it (right). Additional examinations can be performed before and after surgery inside the operating room.

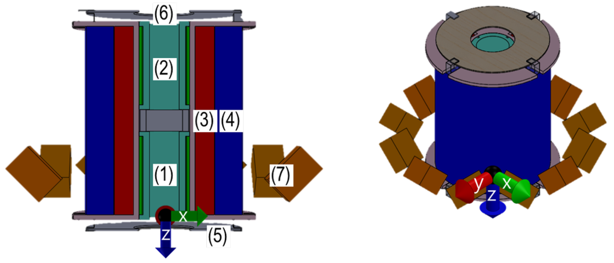

Figure 2: Hardware arrangement of the proposed system: (1) Cylindrical receiver coil, (2) Cylindrical cancellation coil, (3) Excitation coil, (4) Drive coil, (5) Spiral receiver coil, (6) Spiral cancellation coil, (7) Permanent magnets

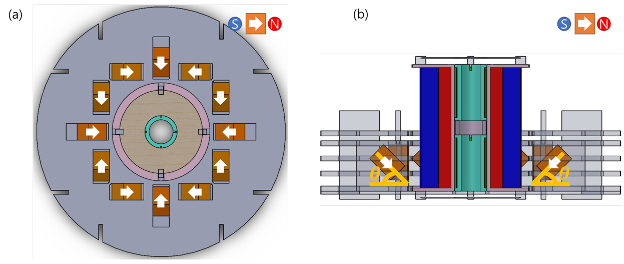

Figure 3: (a) The magnetization direction of the permanent magnet. (b) The angle of the permanent magnets.

To improve the situation, a 2D position marking method through 3D printing has been proposed [9]. In the case of this technology, it is easy to mark patients based on sophisticated data. On the other hand, 3D images acquisition and near-field detection functions in the operating room have been proposed [7,8]. However, they are risky because they require intradermal injection of radioactive materials. Methods using magnetic particles have also been proposed [5,6]. However, they cannot provide accurate depth data, or direct contact with the affected area is inevitable. In particular, most breast cancers exist 1-2 cm under the hairline in the axilla [6]. The already developed device only detects 1 cm area, so prior screening data is required to establish the area where most of the malignant mass is present before exploration can proceed. Therefore, the minimum region of interest for this depth is 2 cm. Thus, a device that can use a safe substance as a contrast agent and return the exact location of the lesion site in real time is needed.

In this paper, we propose a portable single-sided one-dimensional (1D) MPI concept using amplitude modulation (AM) [10]. The proposed system can detect superparamagnetic particles in real-time with a 1D FOV of 2cm. To investigate the influence of magnetic parameters on the magnetic field and magnetic gradient, simulations were performed using COMSOL Multi-Physics software.

II. Material and methods

The device consists of 7 parts. At the center of the device, there is a cylindrical receiving coil (part 1) and a cancellation coil (part 2). The excitation (part 3) and drive coils (part 4) are wrapped around these central coils. Above and below these coils are a spiral receiving coil (part 5) and a cancellation coil (part 6). Permanent magnets (part 7) are arranged as the outermost part of the entire assembly. This can be seen in the cross-section shown in Figure 2. The Field Free Point (FFP) is generated by this permanent magnet array. Then, the drive coil moves the FFP along the z-axis to generate a 1D field of view (FOV). To get a 3D FOV, the instrument is moved mechanically in the xy-plane. The excitation coil is used to oscillate the magnetic nanoparticles (MNPs) that fall in the FOV. The signal generated by these oscillating MNPs is received by the receiving coil. The cancellation coil, which consists of a spiral and a cylindrical coil, is used to prevent the drive field and excitation field feed-through signals, and to match the range of the particle signal with that of the analog-to-digital converter (ADC). The received signal is filtered and pre-amplified (SR560, SRS, Sunnyvale, CA) before digitization. The FOV with 2 cm depth (z-axis) was selected for the presented design [6]. All the currents are applied to the coils through a power amplifier (AE Techron 7224, 1 kW) based on the signal generated by the function generator (KEYSIGHT 33500B Series).

The permanent magnets are placed around the coil to generate the FFP as shown in Figure 3. Three permanent magnets are placed in one bundle as a Hal-Bach array and arranged in four directions. The magnetic concentration area is set towards the inside of the system.

Cylindrical and spiral coils are used simultaneously to receive the signals. Cylindrical coils are good at receiving signals that fall inside them. However, based on Bio-Savart's law, their influence decreases sharply after

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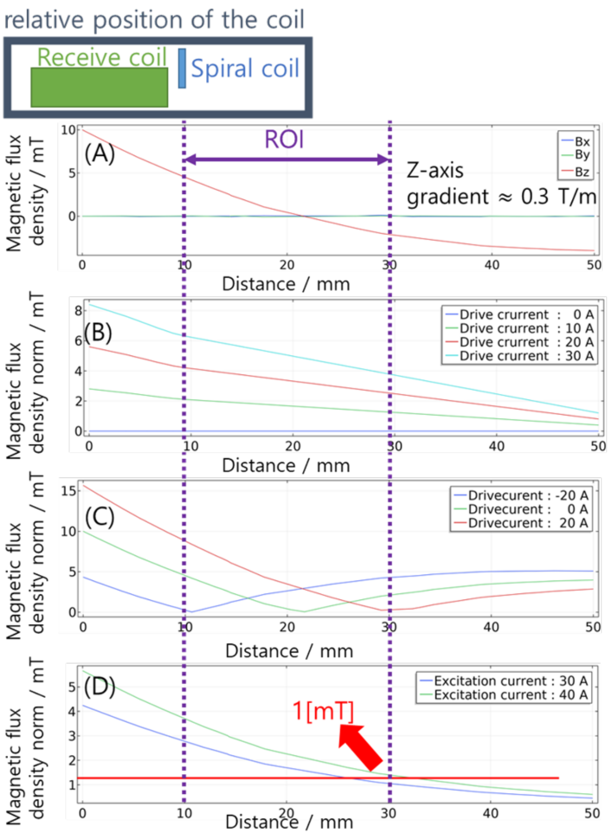

Figure 4: (a) The magnetic flux density along the z axis when only permanent magnets are used. (b) The magnetic flux density normalization from the drive coil. (c) The magnetic flux density normalization from the permanent magnet array and the drive coil put together. (d) The magnetic flux density normalization from the excitation coil

the inflection point. Therefore, a spiral coil with a large diameter is used together with the cylindrical coil to increase the receiving efficiency.

III. Results and discussion

The gradient field generated by the permanent magnets reached 0.3 T/m, which is shown in Figure 4(a). Giving 45° tilt to the magnets, the initial position of FFP is set at the center of the FOV and is easy to move. Receiver coil's sensitivity is shown in Figure 5. Using two types of coils increases this sensitivity. The efficiency of the setup used here is about six times higher at the end of the FOV as compared to that observed when only the cylindrical coil is used. The excitation field reached at least 1mT in all FOV, as shown in Figure 4(d). This 1mT excitation field is sufficient for AM MPI. The drive field was able to cover the entire FOV when the current was in the range of -20 to 10 A, as reflected in Figure 4-(c). Furthermore, the maximum drive field is larger than the

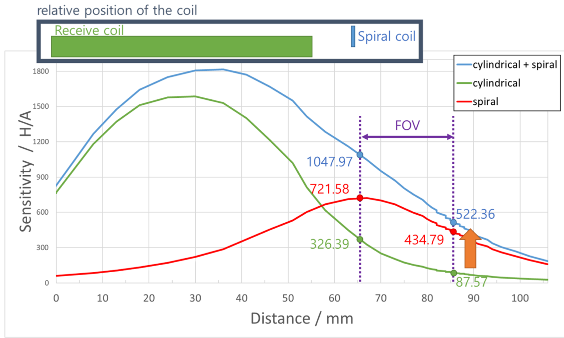

Figure 5: When a current of 1 A is applied to each receiving coil, the sensitivity of the receiving coil is measured through the generated magnetic field. It shows a 6-fold increase at the FOV end.

excitation field, as described in Figure 4(b). Thus, the magnetic system presented in this work is capable of performing its intended task. The system can perform 1D MPI in real-time with frequency of up to 40 kHz. The device has a maximum diameter of 30 cm and a height of 12 cm.

IV. Conclusions

AM method has great potential for miniaturization. Since images can be acquired with a small excitation field, the excitation coil can be placed inside the drive coil. In addition, it is expected that the accuracy of the acquired images will increase through the improved receiving efficiency of the composite coil. Gradient magnetic field can be increased by increasing the strength or number of magnets used. It would be nice if there was a perfect borderline when removing cancer cells, but for safety, some normal cells should also be removed with the affected cells. Therefore, the important thing here is not the image spread but the ability to clearly determine the location of the tumor. The proposed design will be verified in future works.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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