Implantable Multiple-Frequency Inductively-Coupled Coil System for *in vivo* MR Imaging and Spectroscopy of Bioartificial Pancreas at 11.1 T

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Introduction

Tissue engineered (bioartificial) pancreatic constructs are one of the possibilities being explored to alleviate the stress of treatment on diabetic patients. The main criterion in assessing the therapeutic efficacy of this bioartificial pancreas is the successful restoration of the host's glucose regulation. Direct non-invasive *in vivo* monitoring of an implanted pancreatic construct provides correlations between construct function and physiologic effects post-implantation. It also offers the possibility of assessing changes in construct function that may be used to develop early markers of construct failure in advance of the end-point effects e.g., re-institution of hyperglycemia.

Previous *in vitro* and *in vivo* NMR studies were performed on a macro-construct constituted of two concentric disks of agarose hydrogel using a surface coil as an RF antenna and a 4.7 T instrument (1,2). These studies showed great promise. However, these macro-construct designs displayed significant mass transport limitations. To overcome these limitations the number of cells encapsulated within these constructs need to be decreased. However, such decrease may render the NMR experiment impossible due to the low SNR offered by the smaller number of cells. To improve the sensitivity of our NMR experiment to accommodate our target constructs an inductively coupled coil system composed of an loop-gap resonator (3) implantable and inductively coupled to an external coil (4), is being developed to work for imaging and spectroscopy on an 11.1-T horizontal 40-cm clear-bore Magnex magnet equipped with Bruker Biospec console.

A single-frequency implantable coil system working at 470 MHz (11.1T) has given an improvement of ~ 16 times over a surface coil working at 200 MHz (4.7T). However, only one implantable coil can be implanted in a macroconstruct at one time and more than one nucleus would be of interest in this study (^{1}H, ^{31}P, and ^{19}F). Consequently, the development of a multiple-tuned system is necessary. The application of multiple-frequency inductively couple coils opens new avenues to non-invasively monitor tissue engineered constructs.

Methods

The multiple-resonance system was built by adding a tank circuit to a single-resonance design (5) as shown on Fig. 1. This tank circuit composed of a capacitor and an inductor was inserted in parallel with one tuning capacitor of the external coil and the tuning capacitor of the implantable coil. As phosphorus is the least sensitive nuclei, the design of the system was assembled in a way that always optimized the phosphorus frequency over hydrogen and fluorine.

The system was first simulated with GNEC Antenna Analysis software (Nittany, Inc. Riverton, UT) to resonate at 470.74 MHz for ^{1}H, at 190.5 MHz for ^{31}P (Fig. 2). The final design was constructed and tested on the bench. The system was loaded with a sodium phosphate sample for the testing and a vector network analyzer (VNA) HP 8752C (Hewlett Packard, Santa Rosa, CA) was used (Fig. 3). The magnet tests will be performed after the bench testing has been completed. Only two frequencies were used for the system introduced here.

Some further optimizations were also pursued to create the system receive-only. This feature is possible with the addition of a decoupling circuit including 'back-to-back' diodes and an inductor in parallel of one tuning capacitor of both the implantable and external coil. It was initially tested on a ^{1}H single-tuned implantable system combined with a ^{1}H transmit-only volume coil using a water sample.

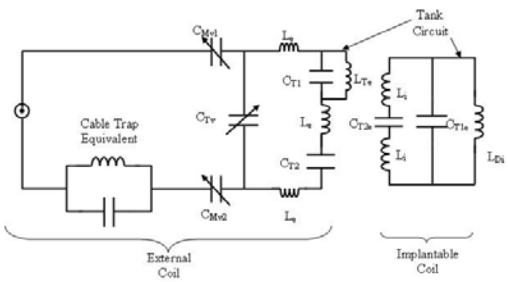

Fig. 1: Multiple-frequency implantable inductively-coupled coil system circuit diagram

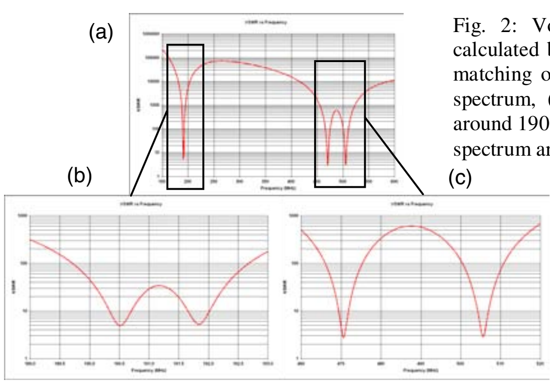

Fig. 2: Voltage standing wave ratio (VSWR) calculated by GNEC and showing the tuning and matching of the system (a) for a wide frequency spectrum, (b) for a narrow frequency spectrum around 190.5 MHz, and (c) for a narrow frequency spectrum around 470.74 MHz.

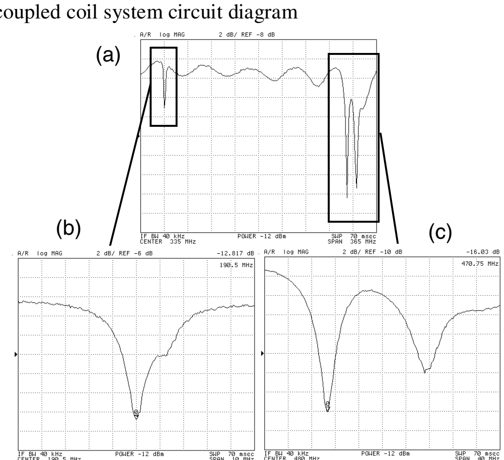

Fig. 3: Result from the VNA showing tuning and matching of the system at (a) both frequencies, (b) 190.5 MHz and (c) 470.74 MHz.

Results and Discussion

The near magnetic field generated by the multiple-frequency inductively coupled system at 190.5 MHz, referred as the low frequency of the system, and at 470.74 MHz, referred as the high frequency of the system, resulted in a similar intensity. The spatial field distribution at low and high frequency was similar to the single-tuned implantable coil system. The network analyzer bench test agreed with the GNEC simulations. Also, the system had a match of -12.8 dB at 190.5 MHz and -16.0 dB at 470.74 MHz (Fig. 3). This is lower than a single-tuned system. The matching network on the multiple-frequency coil can be improved by adding tank circuits to the matching network (5). Using a single tuned inductively coupled coil system we showed that a receive-only system produced better uniformity in the image of the sample compared to a transmit/receive coil system.

Conclusions

The multiple-frequency implantable inductively coupled coil system was successfully constructed to resonate at both frequencies (^{1}H and ^{31}P) as designed from the simulations. Moreover, the receive-only system shows further improvement over the transmit/receive system. Ongoing work is now focused on 1) improving the matching network of the multiple-frequency system, 2) adding a third resonance (443 MHz for ^{19}F) to the system, 3) making the system receive-only for all the frequencies which will require the development of a transmit-only coil working at all the frequencies, and 4) developing coating procedures and embedding the implantable coil in the macroconstruct.

References 1. Stabler CL, *et al*. Cell Transplant. 14. 2005. 2. Stabler CL, *et al*. Tissue Eng. 11. 2005. 3. Hardy WN, *et al*. Rev. Sci. Instrum. 52. 1981. 4. Silver X, *et al*. Magn. Res. Med. 46. 2001. 5. Schnall, MD. NMR Basic Principles and Progress 26: p33-63. Springer-Verlag 1992.