RF communication with implantable wireless device: effects of beating heart on performance of miniature antenna

Olive H. Murphy[1], Alessandro Borghi[1], Mohammad Reza Bahmanyar[1], Christopher N. McLeod[1], Manoraj Navaratnarajah[1,2], Magdi Yacoub[1,2], Christofer Toumazou[1]

[1]Department of Electrical Engineering, Institute of Biomedical Engineering, Centre for Bio-Inspired Technology, Imperial College London, SW7 2AZ, UK
[2]Heart Science Centre, Harefield Hospital, Hill End Road, Harefield, Middlesex UB9 6JH, UK
E-mail: o.murphy@imperial.ac.uk

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The frequency response of an implantable antenna is key to the performance of a wireless implantable sensor. If the antenna detunes significantly, there are substantial power losses resulting in loss of accuracy. One reason for detuning is because of a change in the surrounding environment of an antenna. The pulsating anatomy of the human heart constitutes such a changing environment, so detuning is expected but this has not been quantified dynamically before. Four miniature implantable antennas are presented (two different geometries) along with which are placed within the heart of living swine the dynamic reflection coefficients. These antennas are designed to operate in the short range devices frequency band (863–870 MHz) and are compatible with a deeply implanted cardiovascular pressure sensor. The measurements recorded over 27 seconds capture the effects of the beating heart on the frequency tuning of the implantable antennas. When looked at in the time domain, these effects are clearly physiological and a combination of numerical study and posthumous autopsy proves this to be the case, while retrospective simulation confirms this hypothesis. The impact of pulsating anatomy on antenna design and the need for wideband implantable antennas is highlighted.

1. Introduction: The use of implants for diagnosis and the long term monitoring of chronic illnesses is gaining momentum, with there being many examples recently of emerging technologies [1–3]. The use of deeply implanted sensors within the cardiovascular system has been demonstrated [4–6] and the continuous data available from such sensors is of significant benefit to the patient [7, 8].

Communicating reliably with deeply implanted sensors is a complex task [9, 10]. For subcutaneous implants inductive coupling is used effectively [11, 12]; however, as the technology moves up in frequency and deeper into the body, inductive coupling is no longer a practical means of communication [13]. Planar electromagnetic (EM) waves are used at higher frequencies for deeper implants, but the tissue induced losses are significant [14]. Deeply implanted sensors made wireless using EM waves need a means of radiating and receiving power. Implantable antennas have been widely researched, but relatively few exist for use with deeply implanted sensors [15–18]. In vivo measurements for some subcutaneous or shallowly implanted antennas have been presented [19, 20]; however, few deeply implanted antennas are verified with in vivo measurements [16–18].

One such implantable antenna is the pseudo-normal-mode helical antenna [21] which has been demonstrated to work with a cardiovascular pressure sensor in the left ventricle of the heart for continuous wireless monitoring [5]. This Letter presents the effects of a beating heart on the tuned frequency response of this pseudo-normal-mode antenna and how certain physiological effects can be extracted from the frequency detuning. If the antenna detunes substantially out of the required frequency band, resulting in an impedance mismatch and subsequent power loss, it is not permissible to simply increase the power in order for the implantable sensor to work; for regulatory and safety reasons, the amount of applied power cannot be increased beyond defined limits [22, 23]. Therefore, an understanding of the detuning effects of the beating heart on the frequency response of implantable antennas is very important.

Section 2 will put this research into context while Section 3 will demonstrate the dynamic response of such antennas in a live beating heart. Section 4 shows how the physiological effects are extracted from the detuning parameters and Section 5 will emphasise the importance of designing wideband antennas for use within the body. All experiments described herein were approved by ELPEN Lab and the veterinary authorities of East Attica Region (A. Papalois, April 21st, 2009 Ref. Number 390 and A. Papalois, November 9th, 2010 Ref. Number 330) in accordance with Greek Law (PD 160, A-64, May 1991), European Union Directive (86/609), and the principles of the Helsinki Declaration.

2. Background: Knowing the localised pressure in any of the chambers of the heart is of vital importance in determining a number of heart diseases. The pressure within the right ventricle (RV) is especially important in diagnosing pulmonary hypertension, right ventricular ischemia and tricuspid valvular disease [24]. As well as monitoring the progression of diseases and conditions within the heart, certain pressures are necessary for monitoring the success of heart transplants or the effectiveness of left ventricle assist devices. Having a wireless method of monitoring this pressure removes the need for catheterisation and allows the patient to have freedom of movement, while also providing the clinician with continuous pressure readings [25–27].

The cavity or vessel into which the pressure sensor is placed determines the required geometry of the appropriate antenna. For the RV, a miniature pseudo-normal-mode helical antenna is sufficiently small, and circular polarisation ensures that the exact position of the implant is not required when communicating with an external antenna, which can then be linearly or circularly polarised. While the viability of such an antenna has already been proven [5, 21], the variability of the frequency response will be demonstrated in the following sections through analysis of dynamic measurements, taken over a period of time.

Two implantable pseudo-normal-mode helical antennas of different geometries were surrounded with insulation (non-conductive epoxy), the thickness of which is also fundamental to the tuning [21]. The antennas were designed to work in the short range devices frequency band (863–870 MHz) using three-dimensional

Table 1 Pseudo-normal-mode helical antenna geometry

Outer diameter (*OD*)	3 mm	2 mm
Pitch (*P*)	0.5 mm	0.5 mm
Wire diameter (*WD*)	0.33 mm	0.33 mm
No. turns (*N*)	6.6	10
Axial length (*AL*)	3.3 mm	5 mm

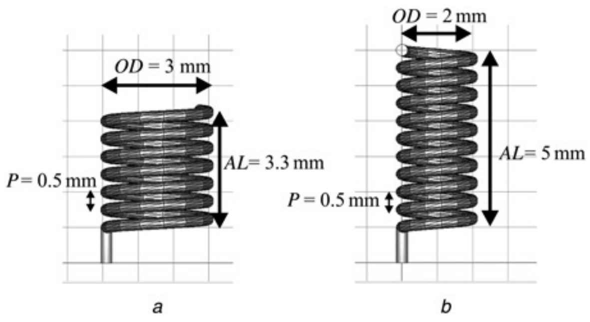

Figure 1 *Geometry of pseudo-normal-mode helical*
a 3 mm antenna
b 2 mm antenna

(3D) EM software [28], where the maximum allowed power levels are predefined up to a maximum of 500 mW [22]. They were then tested in electromagnetically correct bio-phantom [29] and subsequently retuned accordingly. Table 1 shows the geometries of both antennas, which can be also seen in Fig. 1.

3. Dynamic in vivo measurements: During the in vivo testing process, the 3 mm antenna was placed within the RV of three different live, but anesthetised, porcine (30 kg landrace) test subjects – Animal 1, Animal 2 and Animal 3; while the smaller 2 mm antenna was placed within the right atrium (RA) of just one porcine test subject – Animal 3. The procedure was carried out for each animal in turn. The chests were stitched closed and the protruding co-axial cables can be clearly seen for Animal 3 in Fig. 2.

Once the animal was deemed medically stable, the co-axial cables are connected to a Rohde and Schwarz ZVL Vector Network Analyser (VNA) [30] which is remotely controlled to capture the reflection co-efficient (S_{11}) of the implanted antennas. The VNA is programmed to carry out 240 sweeps of S_{11} over a 27 second time-frame, with 201 data points per sweep. In doing so, the stability of the antennas over time and for multiple heartbeats is recorded. The data are imported into Matlab and subsequently smoothed to remove instrument noise, then remaining data points are interpolated to add more resolution.

Fig. 3 shows how the frequency shifts against time for a 3 mm antenna in Animal 1, whereas Fig. 4 shows the frequency shift for the 2 mm antenna in Animal 3. The minima for each sweep are recorded, the mean calculated and the difference between the mean and each minima plotted against time for all of the implanted antennas in Figs. 5–8.

Figure 2 *Landrace pig with 3 and 2 mm antenna within the heart – coaxial cables visible*

4. Analysis: For an antenna to function efficiently, the frequency response should be stable and have a reflection co-efficient (S_{11}) of <−10 dB over the frequency band of interest. Figs. 3 and 4 show that the response is not stable but that the S_{11} criteria is met, as the antenna is sufficiently wideband. The instability indicates that the environment surrounding the antenna is changing and it is interesting to know if any other information can be determined from the frequency variation.

It is clear that the frequency minima are moving with a predefined pattern; therefore an FFT is performed on this data to ascertain the occurrence of the patterns. Figs. 9–12 show that the detuning of the frequency response of the antenna occurs with a regular pattern which can be divided into three distinct frequency bands. Each band corresponds to a particular physiological phenomena corresponding

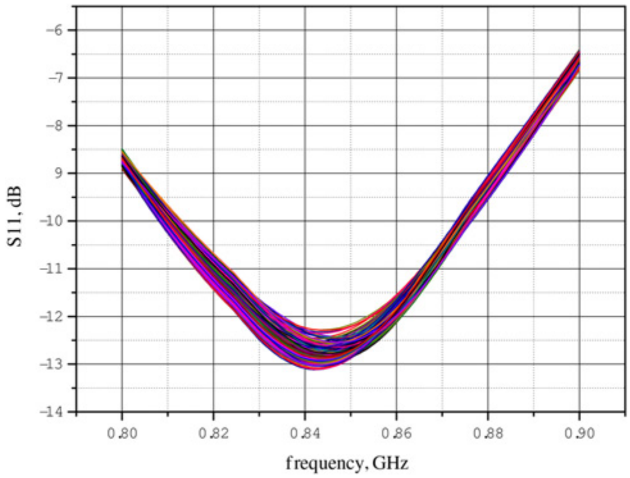

Figure 3 *Variation of the S_{11} of 3 mm antenna over 27 s in Animal 1*

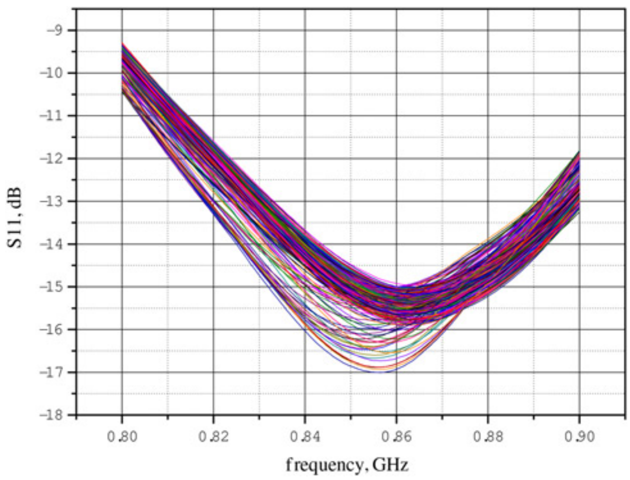

Figure 4 *Variation of the S_{11} of 2 mm antenna over 27 s in Animal 3*

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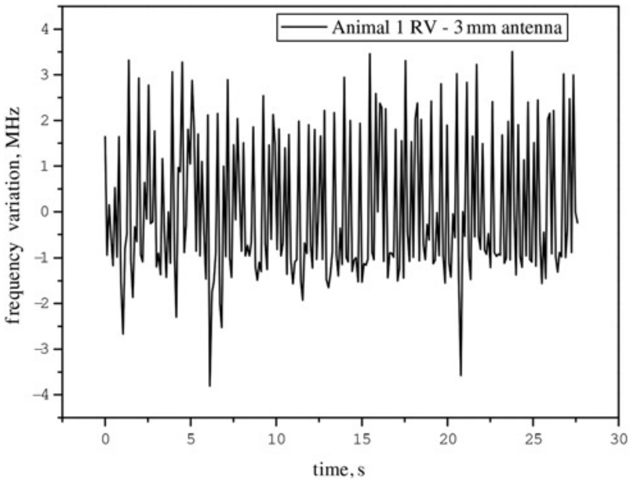

Figure 5 *Frequency variation against time of 3 mm antenna in the RV of Animal 1*

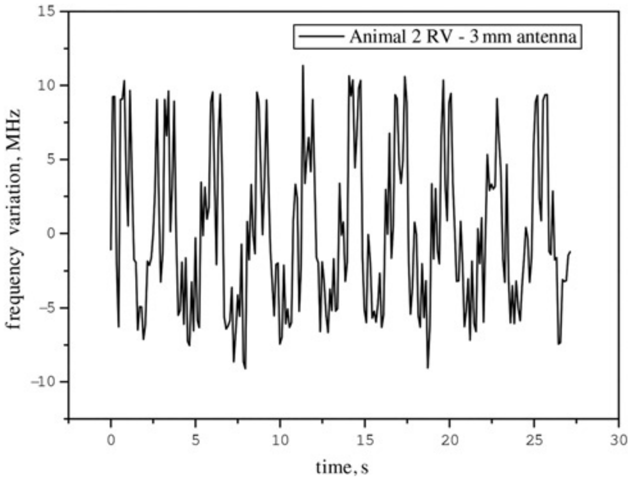

Figure 6 *Frequency variation against time of 3 mm antenna in the RV of Animal 2*

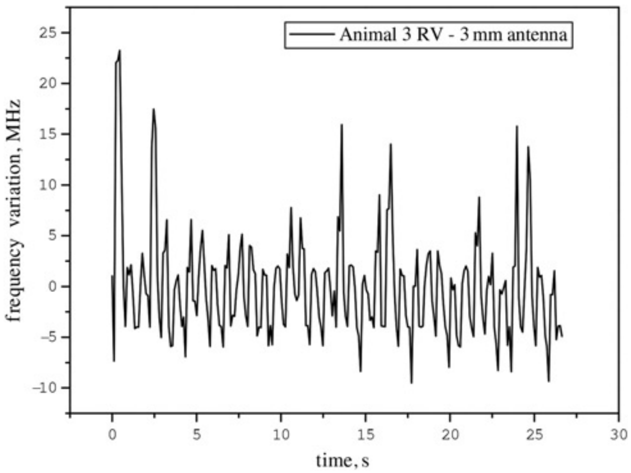

Figure 7 *Frequency variation against time of 3 mm antenna in the RV of Animal 3*

to beats per minute (BPM). For each animal and cavity within the heart, it can be seen that there is one dominant effect, either from breathing, the heart beating or other phenomenon.

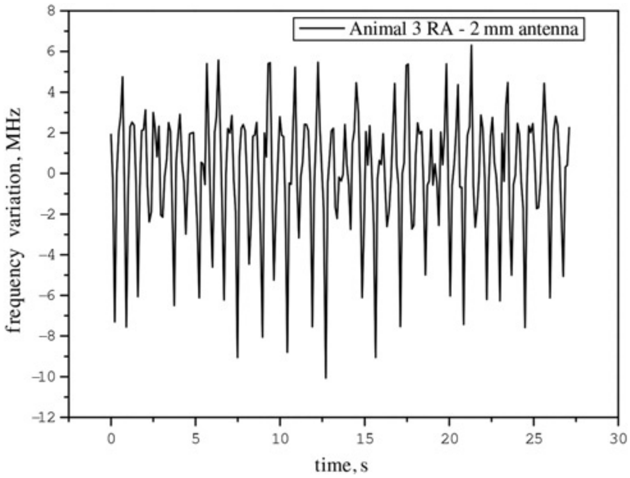

Figure 8 *Frequency variation against time of 2 mm antenna in the RA of Animal 3*

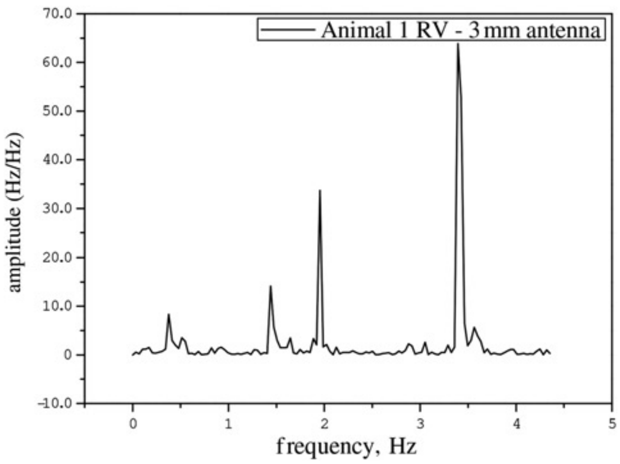

Figure 9 *Periodogram of the frequency content of the signal for the 3 mm antenna in the RV of Animal 1*

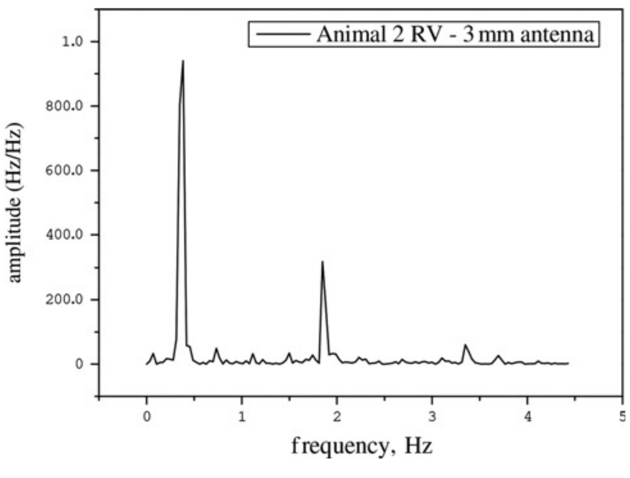

Figure 10 *Periodogram of the frequency content of the signal for the 3 mm antenna in the RV of Animal 2*

It is proposed that the higher frequency component is a suspected sinus tachycardia with a 3:1 block in Animal 1, with the possibility of a higher order harmonic of the heart beat occurring in the other

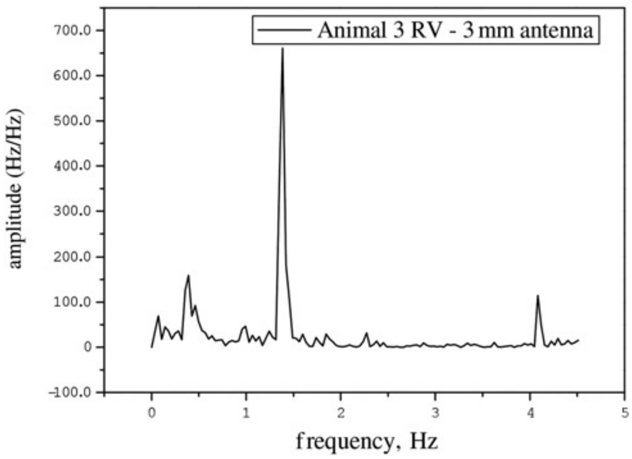

Figure 11 *Periodogram of the frequency content of the signal for the 3 mm antenna in the RV of Animal 3*

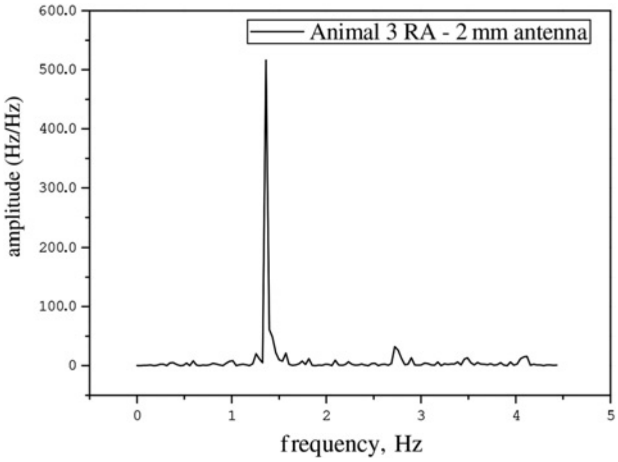

Figure 12 *Periodogram of the frequency content of the signal for the 2 mm antenna in the RV of Animal 3*

animals. All effects: breathing, heart rate and arrhythmia result in a movement of the heart and a change of the environment surrounding the antenna. To see what actually surrounds the antennas, the antennas are explanted from Animal 3 as can be seen in Figs. 13 and 14.

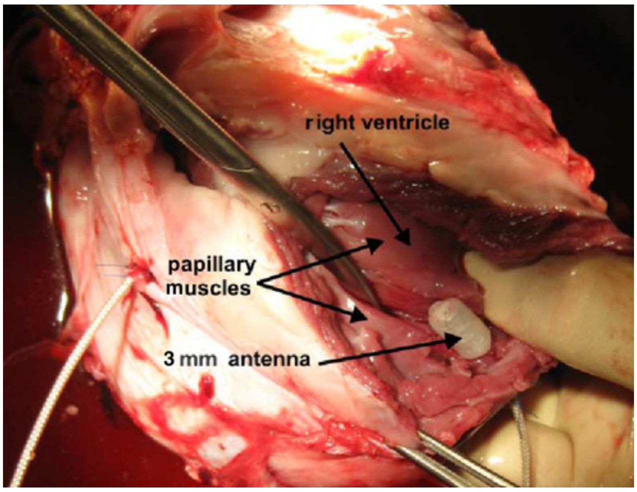

Figure 13 *3 mm antenna about to be explanted from the RV of Animal 3*
Papillary muscles clearly visible

The 3 mm antenna in the RV was located very low in the apex and, as can be seen in Fig. 13, surrounded by not only heart tissue and blood, but also papillary muscles which activate during every heartbeat. The conductivity and permittivity of muscle differ by >10% to heart and blood according to published data [29] and although the heart is a muscle, they are categorised differently in terms of their EM characteristics. The variation in conductivity will not affect the frequency to the same extent as the variation in permittivity as expected [31]. It can be shown by simulation that the same 3 mm antenna surrounded by heart can move in frequency by 3 MHz when surrounded by muscle. In fact, simulations show that when the same antenna is half in heart and half in muscle, the frequency shift is 4 MHz.

For the 2 mm antenna in the RA, as can be seen in Fig. 14, it is highly likely that it was very close to (if not across) the tricuspid valve during the measurements. Once again, the permittivity of the valve is significantly different to that of heart tissue and is composed of different types of collagen [32] it is extremely difficult to simulate based on current published anatomical bio-phantom data [29]. The closest published data is on tendons which are also Type I collagen with a difference in permittivity of ≈30%; therefore detuning would be expected if the antenna is surrounded by the valve instead of heart tissue.

As part of the lungs sit outside the heart and during every breath they expand and collapse around the heart, the change in this environment, even though some distance from the antenna, can also have some influence, and the simulated effect is also about 2 MHz. None of these effects happen in isolation so a cumulative effect can be seen in the frequency detuning of the implantable antennas. To date, EM modelling of large areas of fine anatomical details, as well as dynamic heart movement, is not feasible, and it should be noted that, while simulations are a good starting point, the current published data on heart tissue is from freshly killed (2 hours) bovine samples, so intrinsically, this dead tissue will be different to live tissue and unfortunately no data exists for valves. The best solution is to ensure that any narrowband antennas are placed in a

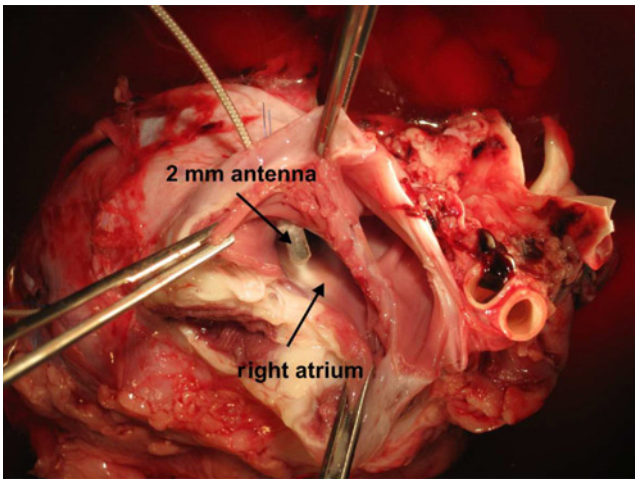

Figure 14 *2 mm antenna about to be explanted from the RA of Animal 3*

Table 2 Frequency content

Band	Freq., Hz	BPM	Cause	Position
1	0.35–0.38	21–22.8	breathing	Animal 2 RV
2	1.38–1.85	82.8–111	beating heart	Animal 3 RV Animal 3 RA
3	3.3–4.0	198–240	arrhythmia	Animal 1 RV

stable environment, namely far from valves and moving structures, or ensure that the antenna response is sufficiently wideband to ensure that such deviations will not have a significant impact on the impedance matching [5]. It can be argued that guaranteeing the precise placement by surgeons of wired antennas is extremely difficult because of anatomical differences between test subjects, and lack of guidewires or imaging, however, with practice, the frequency variation itself can be used as an aid to locating a stable position. For implants, a sensor and antenna, radio-paque markers should be used for imaging to help with placement. All future experimentation should also ensure that any pre-existing cardiac conditions are identified prior to implantation so that they can be eliminated if highlighted during analysis.

5. Conclusions: The empirical measurements presented in this Letter are the first dynamic measurements from the heart of a living swine, and highlight the importance of understanding the relationship between the frequency response of an antenna and the impact of the pulsating cavity into which the antenna is placed. It has been shown that, once an antenna is sufficiently wideband to allow detuning, the impact on the power budget through impedance mismatch is minimal [5, 21]; however, it is obvious that if the antenna is narrowband, detuning out of band will result in power loss which, in turn, can lead to loss of accuracy. Any narrowband antenna design should only be used in a highly stable implant location. It has been shown that the detuning occurred with a regular pattern, which had a physiological cause depending on its particular location within the heart.

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7 References

[1] Chow E.Y., Morris M.M., Irazoqui P.P.: ‘Implantable RF medical devices: the benefits of high-speed communication and much greater communication distances in biomedical applications’, *IEEE Microw. Mag.*, 2013, **14**, pp. 64–73

[2] Kiourti A., Psathas K.A., Nikita K.S.: ‘Implantable and ingestible medical devices with wireless telemetry functionalities: a review of current status and challenges’, *Bioelectromagnetics*, 2014, **35**, pp. 1–15

[3] Toennies J.L., Tortora G., Simi M., Valdastri P., Webster R.J.: ‘Swallowable medical devices for diagnosis and surgery: the state of the art’, *Proc. Inst. Mech. Eng. C, J. Mech. Eng. Sci.*, 2010, **224**, pp. 1397–1414

[4] Abraham W.T., Adamson P.B., Bourge R.C., *et al.*: ‘Wireless pulmonary artery haemodynamic monitoring in chronic heart failure: a randomised controlled trial’, *Lancet*, 2011, **377**, pp. 658–66

[5] Murphy O.H., Bahmanyar M.R., Borghi A., *et al.*: ‘Continuous in vivo blood pressure measurements using a fully implantable wireless SAW sensor’, *Biomed. Microdevices*, 2013, **15**, pp. 737–49

[6] Crozier I., Smith W.: ‘Modern device technologies’, *Heart Lung Circ.*, 2012, **21**, pp. 320–7

[7] Palaniswamy C., Mishkin A., Aronow W.S., Kalra A., Frishman W. H.: ‘Remote patient monitoring in chronic heart failure’, *Cardiol. Rev.*, 2013, **21**, pp. 141–50

[8] Varma N., Ricci R.P.: ‘Telemedicine and cardiac implants: what is the benefit?’, *Eur. Heart J.*, 2013, **34**, pp. 1885–95

[9] Bashirullah R.: ‘Wireless implants parameterization of hardware challenges’, *IEEE Microw. Mag.*, 2010, pp. 14–23

[10] Clifford G.D., Clifton D.: ‘Wireless technology in disease management and medicine’, *Annu. Rev. Med.*, 2012, **63**, pp. 479–92

[11] Theodoridis M.P., Mollov S.V.: ‘Distant energy transfer for artificial human implants’, *IEEE Trans. Biomed. Eng.*, 2005, **52**, pp. 1931–1938

[12] Catrysse M., Hermans B., Puers R.: ‘An inductive power system with integrated bi-directional data-transmission’, *Sensors Actuators A, Phys.*, 2004, **115**, pp. 221–229

[13] Uei-Ming J., Ghovanloo M.: ‘Design and optimization of printed spiral coils for efficient transcutaneous inductive power transmission’, *IEEE Trans. Biomed. Circuits Syst.*, 2007, **1**, pp. 193–202

[14] Poon A.S.Y., O’Driscoll S., Meng T.H.: ‘Optimal frequency for wireless power transmission into dispersive tissue’, *IEEE Trans. Antennas Propag.*, 2010, **58**, pp. 1739–1750

[15] Zhi N.C., Guan C.L., See T.: ‘Transmission of RF signals between MICS loop antennas in free space and implanted in the human head’, *IEEE Trans. Antennas Propag.*, 2009, **57**, pp. 1850–1854

[16] Chow E.Y., Chin-Lung Y., Chlebowski A., Sungwook M., Chappell W.J., Irazoqui P.P.: ‘Implantable wireless telemetry boards for in vivo transocular transmission’, *IEEE Trans. Microw. Theory Tech.*, 2008, **56**, pp. 3200–3208

[17] Takahata K., Gianchandani Y.B., Wise K.D.: ‘Micromachined antenna stents and cuffs for monitoring intraluminal pressure and flow’, *IEEE J. Microelectromech. Syst.*, 2006, **15**, pp. 1289–1298

[18] Chow E.Y., Yuehui O., Beier B., Chappell W.J., Irazoqui P.P.: ‘Evaluation of cardiovascular stents as antennas for implantable wireless applications’, *IEEE Trans. Microw. Theory Tech.*, 2009, **57**, pp. 2523–2532

[19] Kiourti A., Psathas K.A., Lelovas P., Kostomitsopoulos N., Nikita K. S.: ‘In vivo tests of implantable antennas in rats: antenna size and intersubject considerations’, *IEEE Antenn. Wirel. Propag. Lett.*, 2013, **12**, pp. 1396–1399

[20] Karacolak T., Cooper R., Butler J., Fisher S., Topsakal E.: ‘In vivo verification of implantable antennas using rats as model animals’, *IEEE Antenn. Wirel. Propag. Lett.*, 2010, **9**, pp. 334–337

[21] Murphy O.H., Mcleod C.N., Navaratnarajah M., Yacoub M.H., Toumazou C.: ‘A pseudo-normal-mode helical antenna for use with deeply implanted wireless sensors’, *IEEE Trans. Antennas Propag.*, 2012, **60**, pp. 2419–2423

[22] EN 300 220-1 – Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment to be used in the 25 MHz to 1000 MHz frequency range with power levels ranging up to 500 mW; Part 1: Technical characteristics and test methods, 2013, **1**, pp. 1–73

[23] Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz), International Committee for Non-Ionizing Radiation Protection (ICNIRP), 1998, http://www.icnirp.de/documents/emfgdl.pdf

[24] Voelkel N.F., Quaife R.A., Leinwand L.A., *et al.*: ‘Right ventricular function, failure: report of a National Heart, Lung, and Blood Institute working group on cellular and molecular mechanisms of right heart failure’, *Circulation*, 2006, **114**, pp. 1883–91

[25] White W.B.: ‘Expanding the use of ambulatory blood pressure monitoring for the diagnosis and management of patients with hypertension’, *Hypertension*, 2006, **1**, pp. 14–15

[26] Slaughter M.S., Pagani F.D., Rogers J.G., *et al.*: ‘Clinical management of continuous-flow left ventricular assist devices in advanced heart failure’, *J. Heart Lung Transplant*, 2010, **29**, pp. S1–S39

[27] Wieselthaler G.M., Schima H., Dworschak M., *et al.*: ‘First experiences with outpatient care of patients with implanted axial flow pumps’, *Artif. Organs*, 2001, **5**, pp. 331–335

[28] CST, Computer Simulation Software, http://www.cst.com/Products/CSTMWS

[29] Gabriel S., Lau R.W., Gabriel C.: ‘The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz’, *Phys. Med. Biol.*, 1996, **41**, pp. 2251–69

[30] R&S ZVL Vector Network Analyzers, http://www2.rohde-schwarz.com/product/ZVL.html

[31] Wheeler H.A.: ‘Small antennas’, *IEEE Trans. Antennas Propag.*, 1975, **23**, pp. 462–469

[32] Aupperle H., März I., Thielebein J., Kiefer B., Dinges G., Schoon H.-A.: ‘Distribution of extracellular matrix components in normal and degenerated canine tricuspid valve leaflets’, *J. Comp. Pathol.*, 2009, **141**, pp. 41–51