CORRELATION OF IN-LINE AND TRANSVERSE FORCE OF THE PECTORALIS MAJOR TO DETERMINE MECHANICAL LOADINGS ON SUB-MUSCULAR PECTORAL PACEMAKER IMPLANTS

Thomas Franz, Michael Hamman de Vaal, James Neville, Jacques Scherman, Micah Litow, Peter Zilla

Cardiovascular Research Unit, Chris Barnard Department of Cardiothoracic Surgery, University of Cape Town, Cape Town, South Africa; email: thomas.franz@uct.ac.za

Cardiac Rhythm Disease Management, Medtronic Inc, Minneapolis, MN, USA

Neuromodulation Division, Medtronic Inc, Minneapolis, MN, USA

SUMMARY
We investigated the intra-species proportionality of in-line force and transverse reaction force of the Pectoralis major for the characterization of mechanical in vivo loadings on pectoral implants. Two Chacma baboons (23.9 ± 1.2 kg) received bilaterally one chronic and one acute pectoral sub-muscular instrumented pacemaker (IPM) implant. The Pectoralis major muscle was electrically stimulated and resulting in-line and transverse muscle force were measured. The correlation of in-line and transverse force of the Pectoralis major was studied using linear regression analyses. The proportionality of in-line and transverse force of the Pectoralis major was found to be subject-specific (R^2 = 0.17, p < 0.003). Including morphometric parameters, i.e. length along line of action, width over implant and stress, in the regression analysis provided a strong intra-species correlation between in-line and transverse force (R^2 = 0.71, p < 10^-7). The novel intra-species correlation provides a tool towards the characterization of mechanical in vivo loading conditions of pectoral device implants.

INTRODUCTION
Implantable pulse generators (pacemakers) have been used extensively for the treatment of cardiac arrhythmias due to significantly increased clinical benefits compared to purely pharmacological treatment [1] and reduced mortality in high-risk patient populations [2]. Technological advances have offered the potential to reduce the dimensions of implantable pacemakers [2-4]. Together with clinical advances, this development increases the feasibility of implantable pacemakers for use in younger patients [3, 5, 6] which are generally more active than the traditional target group of elderly patients. Smaller structures and elevated levels of activity translate into increased mechanical demands on the implants and smaller margins for structural reliability. The detailed knowledge of the mechanical in vivo use conditions of implantable pacemakers becomes more important for the device design in order to ensure structural integrity and device reliability. We recently demonstrated the feasibility of a system for pre-clinical in vivo measurement of transverse compressive loadings on sub-muscular pectoral pacemaker implants [7]. The current study focused on the investigation of a relationship between the force of the Pectoralis major muscle in line of its action, i.e. in-line force, and the transverse force exerted on a pacemaker structure implanted in the sub-muscular position. The in-line force of the Pectoralis major muscle can be assessed with surface-based measurement techniques such as electro myography. A correlation between in-line and transverse force of the Pectoralis major may as such allow for the non-invasive characterization of in vivo mechanical conditions of pacemaker implants in volunteers and patients.

METHODS
Measurement of Muscle Force: The in-line force of the Pectoralis major was measured with a custom buckle transducer with closed rectangular frame (66 x 100 mm, 4 x 4 mm cross-section), removable cross bar and two foil strain gauges (Vishay Micro Measurements Group, Malvern, PA). The transverse force of the Pectoralis major was measured with a wireless in vivo measurement system comprising an implantable instrumented pacemaker (IPM) and a radio-frequency control and data acquisition system [7]. The IPM (dimensions: 64 x 61 x 11 mm) resembled a typical commercial pacemaker housing and contained 6 custom contact force sensors (Tekscan, Boston, MA), a 3-axis accelerometer (Freescale Semiconductor, Tempe, AZ), RF transceiver, micro-controller and battery.

In vivo Experiments: The study was approved by the research ethics committee of the University of Cape Town. Under full anesthesia, two senescent Chacma baboons (implant mass: 23.9 ± 1.2 kg) received one IPM unilaterally in the upper pectoral region in sub-muscularly position using standard surgical techniques for the implantation of cardiac pacemakers. Ten weeks after implantation, the Pectoralis major muscle was exposed and isolated from surrounding soft tissue with the animals under full anesthesia. The buckle transducer was attached to the Pectoralis major utilizing two incisions in fiber direction of the muscle extending from the IPM implant towards the muscle insertion. Adhesive surface electrodes (Medtronic Inc, Minneapolis, MN) were attached to the exposed Pectoralis major near its origin and insertion for electrical stimulation. Constant frequency train (CFT) stimulation of the Pectoralis major was performed using a PULSAR 6bp bipolar stimulator (FHC Inc, Bowdoinham, ME). The muscle received trains (2000 pulses, duration: 53 μs, interval: 203 μs) of electrical current of constant, discrete amplitude of 3, 5, 7, 9, 11, 15, 17, 21, 23, 27, 31, 33, and 35 mA in one of two pre-determined randomized orders. The arm of the animal was constrained in anatomical position; the
shoulder complex was left to move freely. The contractile in-line force $F_{IL}$ and the transverse force $F_T$ of the stimulated muscle was measured with the buckle transducer and IPM, respectively. At the same occasion, identical procedures were performed on the alternate pectoral side with an acute IPM implant for both animals. Post-mortem, the following dimensions of the Pectoralis major were measured: length along estimated line of action $L_m$, thickness $t_{m,cb}$ and width $w_{m,cb}$ at crossbar of buckle transducer and width over IPM implant $w_{m,IPM}$. Mass $M_m$ and volume $V_m$ of the muscle were recorded after excision.

**Correlation of In-line Force $F_{IL}$ and Transverse Force $F_T$:** Simple and multiple linear regression (SLR and MLR) analyses were performed to evaluate the relationship between $F_{IL}$ and $F_T$ of the Pectoralis major and to identify significant parameters. $F_T$ was defined as response. $F_{IL}$ and the morphometric muscle parameters $L_m$, $t_{m,cb}$, $w_{m,cb}$, $w_{m,IPM}$, $M_m$, and $V_m$ were regarded as regressors. To account for the increase of the degree of freedom due to addition of regressors, an adjusted coefficient of determination, $R^2_{adj}$ was used.

**RESULTS AND DISCUSSION**

The in-line force $F_{IL}$ of the Pectoralis major recorded during electrical stimulation varied in the ranges of 0.9-60.9 N (447C) and 3.6-85.0 N (449C) for the chronic IPM implants. The force ranges were larger for the acute implants with 30.9-184.3 N (447A) and 1.1-155.1 N (449A), see Figure 1. The transverse force $F_T$ of the Pectoralis major during electrical stimulation was in the range 5.4-9.2 N (447C), 9.2-41.7 N (449A), 9.5-55.8 (447A) and 14.3-90.7 N (449C), see Figure 2. Significant subject-specific correlation ($p < 0.05$) between $F_T$ and $F_{IL}$ was indicated by SLR for each Pectoralis major muscle. The linear regression (trend lines in Figure 2) yielded the following relationships and associated coefficients of determination: $F_T = 0.06 F_{IL} + 5.24$, $R^2 = 0.80$ (447C); $F_T = 0.99 F_{IL} + 8.63$, $R^2 = 0.97$ (449C); $F_T = 0.17 F_{IL} + 5.03$, $R^2 = 0.56$ (447A); and $F_T = 0.23 F_{IL} + 7.47$, $R^2 = 0.96$ (449A). The generalized intra-species correlation was evaluated with SLR and MLR analyses on the entire data set of $F_T$ and $F_{IL}$ ($n=51$) from all four experiments (447C, 447A, 449C and 449A). The strongest correlation ($R^2 = 0.71$, $R^2_{adj} = 0.68$) was indicated for the following regression equation:

$$F_T = -1055.78 - 0.24F_{IL} + 3.24L_m + 5.95w_{m,IPM} + 434.62\sigma_m$$

It remained uncertain whether maximum levels of $F_{IL}$ were reached during the electrical stimulation. The maximum electrical current did not always yield the largest magnitude of $F_{IL}$. Accelerated muscle fatigue due to the CFT stimulation compared to variable frequency train stimulation may have played a role. However, CFT stimulation was chosen as it is used in most current systems for functional electrical stimulation and generally provides a more physiological stimulation pattern.

**CONCLUSIONS**

By combining electrical stimulation of the Pectoralis major and in-line force measurement using a buckle transducer with the newly developed in vivo measurement of the transverse force of Pectoralis major, a subject-specific proportionality and an intra-specific correlation between in-line force and transverse force of the Pectoralis major could be established. The intra-species relationship may offer potential for new insights in the biomechanics of pectoral pacemaker implants in patients.

**REFERENCES**