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In and ex-vivo myocardial tissue temperature monitoring by combined infrared and ultrasonic thermometries

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Abstract

The success of cardiac surgery essentially depends on tissue preservation during intervention. Consequently a hypothermic cardioplegia is applied in order to avoid ischemia. However, myocardial temperature is not monitored during operation. The aim of this study is then to find a relevant and simple method for myocardial global temperature estimation in real time using both ultrasounds and infra-red thermography. In order to quantify the sensitivity of ultrasonic velocity to temperature, a 2.25 MHz ultrasonic probe was used for ex-vivo tests. Pig myocarids (n=25) were placed in a thermostatically-controlled water bath and measurements of the ultrasound velocity were realized from 10 to 30 °C. The results of this study indicate that the specificity and sensitivity of the ultrasonic echo delay induced by the modification of temperature can be exploited for in-depth thermometry. In parallel, for TIR experiments, a bolometer was used to detect the myocardium surface thermal evolution during in-vivo pig heart experiments. Hypothermic cardioplegic solutions were injected and infra-red surface imaging was performed during one hour. In the near futur, the correlation of the ultrasound and the infrared measurements should allow the real time estimation of the global temperature of the heart. The final objective being to realize in vivo measurements on human hearts, this information may have a very high importance in terms of per-operation inspection as well as decision making process during medical interventions.

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1. Introduction

Tissue temperature control during cardiac surgery is crucial for myocardial protection. Currently, the majority of open-heart operations requires cold cardioplegia administrations in order to improve tissue preservation and decrease the number of post-operation complications and mortality [1]. The heart is stopped and its temperature lowered to minimize oxygen requirements. However, environmental impacts counteract the cardioplegia action leading to tissue warming and increased ischemia. Moreover, the heart temperature is not monitored and its evolution is only controlled

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through a cardioplegia protocol [2]. The aim of this study is to propose a relevant and simple method allowing the real time estimation of the myocardial global temperature. Ultrasonic measurements can then offer informations revealing in depth myocardial thermal characteristics [3, 4] and the influence of temperature on the ultrasonic parameters of tissues has been largely exploited in particular to monitor hyperthermia therapy [5, 6, 7, 8]. In parallel, TIR imaging is a non invasive and safe method allowing the assessment of the changes of the myocardial surface temperature in real time, and experiments have already been performed allowing per-operative inspections [9, 10, 11]. The aim of this work is to couple these two methods to allow, in a multi-physical analysis, the monitoring of the myocardial thermal behavior.

2. Materials and Methods

2.1. Ex-vivo measurements of myocardial tissue temperature by ultrasounds

To quantify the temperature sensitivity of the ultrasound velocity in the myocardial tissue, preliminary experiments were realized on ex-vivo samples. Each sample was positioned in a thermostatically-controlled water bath and pulse-echo measurements were performed thanks to a 2.25 MHz ultrasonic probe. The shifts in the time of arrival (Δt) of the ultrasonic echoes were then monitored while varying the temperature by steps of 5 °C. To match the surgical conditions, the experimental temperature was chosen to be ranging between 10 and 30 °C. An indentation technique was then applied to allow velocity measurements [12]: the Δt of ultrasonic pulses are recorded for several vertical positions of the probe inside the myocardial tissue. Performing these experiments on a large number of samples ($n = 15$) allowed the identification of an experimental law linking the ultrasound velocity to the myocardial temperature. With this knowledge, the method is then adapted to avoid sensor displacements during cardiac surgery. Given the initial temperature, the heart thickness was estimated taking advantage of the previous law and simple echo measurements were performed on integral myocardia ($n=25$) allowing the monitoring of the tissue temperature changes.

2.2. In vivo measurements of myocardial tissue surface temperature by thermal infra-red imaging

Experiments were realized on female pigs ($n = 2$) weighting between 30 and 40 kg. The animals received a general anesthesia and an average sternotomy was performed followed by cardiopulmonary bypass between the right atrium and the ascending aorta. The aorta was clamped and a blood cardioplegia was applied. The experimental protocol consisted in three parts each including an injection of a 500 mL crystalloid solution (Custodiol, EUSA Pharma, France) and a 20 minute natural warming. The myocardial thermal evolution was studied using an uncooled microbolometer infrared detector (SC-645, FLIR[®] System, USA) positioned at a distance of 50 cm from the prior heart. Image acquisitions and processing were performed thanks to Labview[®] programs developed specifically for the study. Experimental environmental conditions allowed the estimation of a 0.5 °C error on the presented results.

3. Results

Figure 1 presents results obtained from ultrasonic experiments performed on myocardial samples. They yield the definition of an experimental law linking the ultrasound velocity to the temperature of the myocardial tissue (Fig. 1a):

$$V(T) = (2.2 \pm 0.33) \cdot T + 1502.6 \pm 12 \quad [\text{m s}^{-1}]. \quad (1)$$

This calibration curve presents a high experimental deviation of $\pm 12 \text{m s}^{-1}$. In accordance with works from the literature [13, 14], 0.5 % of this deviation can be attributed to the muscle fibers' orientation while 1.3% are due to a myocardium heterogeneity (left, right ventricles/atria). Then in a second step, to match surgery constraints, pulse-echo measurements were realized on integral hearts without any probe displacement (Fig. 1a). Thanks to equation (1), they lead to the identification of sensitivity factors k of the myocardial tissue:

$$k = 20.5 \pm 8 \quad [\text{ns/cm/}^\circ\text{C}]. \quad (2)$$

This latter undergoes, for 25 experiments, a high experimental dispersion, illustrated on the histogram of Figure 1b. Mainly due to Fig. 1a experimental deviation and to tissue inhomogeneity, it leads to a possible error of around 3

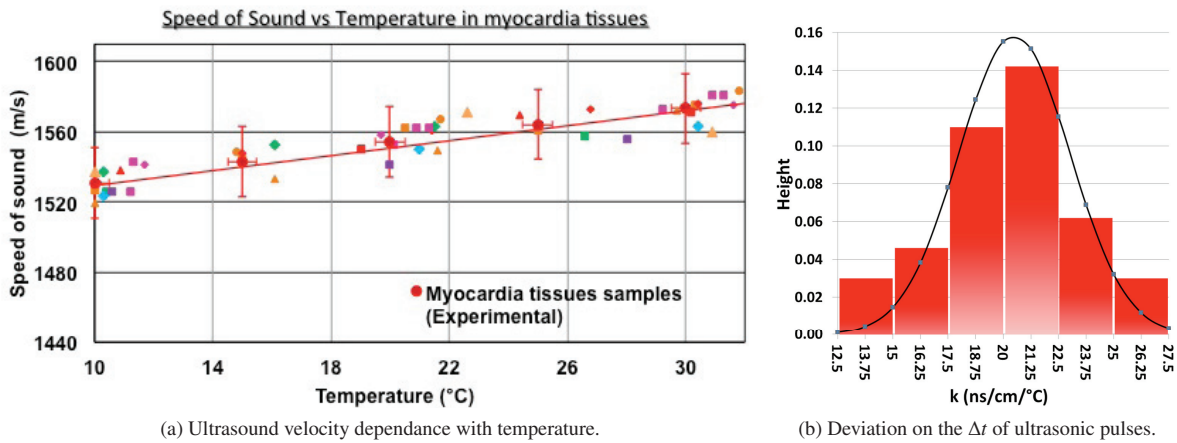
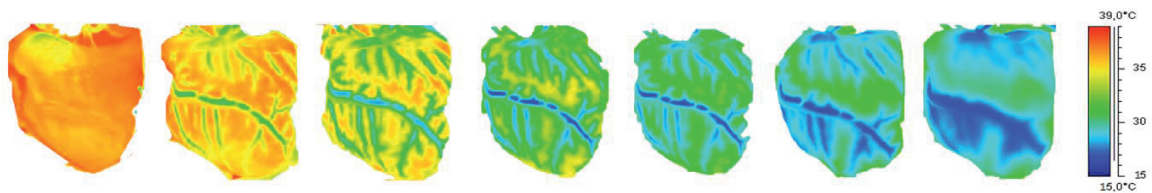
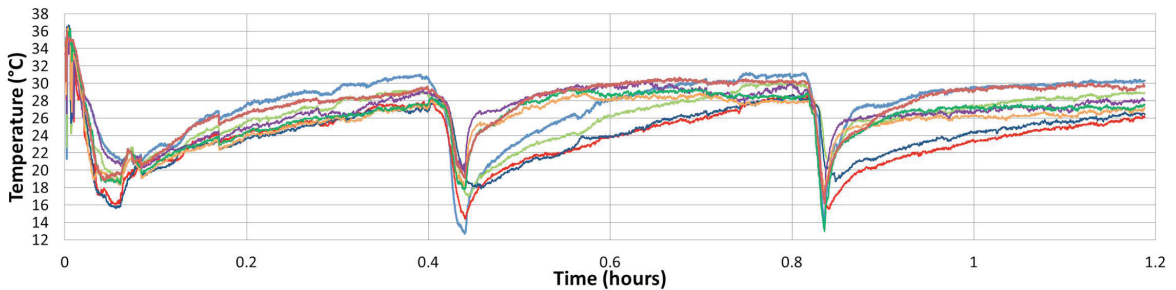


Fig. 1: Results obtained from ultrasonic measurements performed on ex-vivo pig myocardia (n= 40).

degrees on the temperature estimation. This indicates that, while ultrasounds are sensitive to temperature changes of the tissues, the myocardium heterogeneity is too high to allow precise identification of the thermal dynamic of the heart without a complementary calibration. It will be given, in the following thanks to infra-red thermography.



(a) Evolution of the surface temperature of the anterior part of the heart during injection of a hypothermic cardioplegia.



(b) Evolution of the local temperature of 10 points. Measurements performed during 1 h including 3 injections.

Fig. 2: TIR measurements acquired on in-vivo pig myocardia during cardioplegia.

Figure 2 presents the results obtained from TIR measurements performed on in-vivo pig myocardia during cardioplegia. Temperature cartographies of the anterior surface of the heart were obtained for different times (Fig. 2a). They allow the real time observation of the thermal behavior of the heart areas and the distribution of the hypothermic cardioplegia within the coronary arteries. Figure 2b presents the temperature evolution of 10 points chosen on different parts of the myocardia. These results confirm for each cardioplegia the non-homogeneity of the thermal dynamic of the heart. While cardioplegia lower the tissue temperatures to values ranging between 14 and 20 °C, two trends are visible: the right ventricle warms up very quickly and reaches a temperature plateau in less than 10 minutes while the left ventricle needs more than 25 minutes to reach temperatures close to 30 °C.

4. Conclusion

To summarize, ultrasound and TIR experiments were realized revealing the high heterogeneity of the heart tissues and of their corresponding thermal dynamics. They proved that the sensitivity of ultrasonic echo delay induced by the changing temperature of the myocardium can be exploited during surgery to estimate the heart temperature with an evaluated error of around 3 degrees also due to in depth non-uniform thermal repartition. In parallel, TIR imaging is only sensitive to the temperature of the surface of the heart. Taking advantage of the two methods' characteristics, future works will deal with their coupling. TIR imaging will allow the real-time identification of the surface temperatures of the different areas of the myocardium. With this knowledge, ultrasonic measurements will then be performed to obtain in depth characterization. To this aim, models are currently being developed to infer, from a surface temperature calibration, the thermal in depth dynamic of the heart muscle. In vivo measurements are also planned during human heart surgery, the final objective of this work being to propose to the surgeon a decision-making tool.

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