Abstract: The goal of this research was to design and evaluate an infrared (IR) prototype device for the detection of the blood temperature during a surgical operation for coronary bypass implantation. The idea was to study a low cost portable device to be placed near the region of interest.

We chose a pyroelectric sensor for its high quality-cost ratio. Because this kind of sensor detects only a variable infrared source, we used an electromechanical chopper for modulating the radiation. The output signal was analysed using a dedicated electronics; then an acquisition board is employed for processing the signal using a PC.

Prototype assessment was made with laboratory equipment, with an experimental study conducted according to a physical model, and with the preliminary results of in vivo measurements during surgical operation of a little pig.

Introduction

Application of infrared thermograph in cardiac surgery provides important information regarding coronary flow, coronary anatomy and myocardial perfusion and function [1].

In 1985 Papp et al. [2] demonstrated the correlation between coronary flow and epicardial temperature by quantitative infrared thermography of rabbits’ hearts.

Cardiac thermograms were taken with an infrared camera and a hydraulic occluder was used to constrict gradually the left common coronary artery, then the heart perfusion was observed.

In the isolated rabbit’s heart the relation of the decreasing flow to the decrease of mean epicardial temperature was very strict and quasi-linear.

In the 1987 Adachi [3] studied the myocardial perfusion of ten dogs by an infrared imaging system. As in Papp’s experiment, the left coronary artery was occluded to create an ischemia for 90 minutes, then it was opened and the temperature was recorded for 210 min of reperfusion.

As a result of the experiment, the authors found an empiric relation between blood flow in the coronary and superficial temperature.

In an other experiment [1] with dogs was used a cool saline solution injected in the aortic artery to decrease the blood temperature and to observe in which way the system was returned to normal condition.

However, since in cardiac surgery a high value of sensitivity is required, very expensive thermocameras are necessary in all of these experiments.

The aim of this paper is to describe the design of a low cost portable device that could be placed near the region of interest during a surgical operation for coronary bypass implantation.

For the prototype design, the basic theory that we used was the fact that each blood vessel acts like a thermal wave emitter.

We chose a pyroelectric sensor for its high quality-cost ratio. The amplitude of the detected signal is proportional to the energy of infrared radiation emitted by the object, so each peak of this signal corresponds to the relative temperature of the object.

The prototype assessment was made using a laboratory equipment, with an experimental study conducted according to a physical model, and with the preliminary results of in vivo measurements during surgical operation of an animal.

Materials and methods

In general, IR sensors detect the thermal energy emitted by the human body in the form of electromagnetic radiation at a wavelength of infrared region (0.76-100µm) [4].

Total energy emitted and the temperature are related by the Stefan-Boltzman formula:

$$ W = \varepsilon \sigma T^4 $$

where $W$ is the radiant flux density (W/m$^2$), $\varepsilon$ is the emissivity factor, $\sigma$ is the Stefan-Boltzman constant and $T$ is the absolute temperature. The value of $\varepsilon$ for human skin at room temperature is unity, so the human body acts like a black body and the wavelength of the energy peak is at 10µm.

The other important physical phenomenon is the convective heat-transfer between the artery wall and the blood.

In general, blood flow in artery is laminar; neglecting the effect of pulsatile flow [1], the Reynolds number can be calculated by the follow equation:
Re = \frac{vd\rho}{\eta_{\text{blood}}}

(2)

where \( v \) is the blood flow velocity, \( d \) is the vessel diameter, \( \rho \) is the blood density and \( \eta_{\text{blood}} \) is the viscosity; we can find that it’s smaller than the critical value of 2000 \([5]\).

In a coronary artery with a \( d \) of 3 mm, a \( v \) of 0.3 m/s, considering a blood \( \rho \) of 1050 Kg/m\(^3\) and a \( \eta_{\text{blood}} \) of 4 cp, using Eq. (2) results in a Re of 236.35, so the blood flow can be considered a laminar flow.

Pyroelectric sensors act as a thermal transducer, detecting a temperature variation generated by an incident IR radiation through changes in material properties.

A pyroelectric sensing element converts the thermal radiation into the output measurable quantity like charge, voltage or current by pyroelectric effect.

The pyroelectric detectors have a high quality-cost ratio, high sensitivity and low cost manufacturing; for these qualities, they have found many applications such as intruder alarms, fire alarms, chemical analysis, laser detectors, and human information detection.

A pyroelectric device consists of a window, a sensing element, and a readout integral circuit. The window acts like an optical high-pass filter that blocks unwanted wavelengths such as visible lights. In our sensor (IRA-E900 Murata) the window is a 5 \( \mu \)m long pass Silicon filter.

A change in \( \Delta T \) produces a transient change in the surface charge causing a displacement current \( I \) to flow in an external circuit connected to the pyroelectric material:

\[ I = pA \frac{d(\Delta T)}{dt} \]

(3)

where \( p \) is the pyroelectric coefficient and \( A \) is the detector area.

In general, pyroelectric sensors detect only modulated radiations so for using them to measure a continue emission by an infrared source is necessary to modulate the incident radiation with a mechanical chopper, because the sensing element reacts only to changing heat flux.

For our application, emission of IR radiation from the coronary in open heart surgical operation, the incident radiation is periodically chopped in order to generate a continuous output voltage or current.

We proposed an electronic shutter that establishes the chopping frequency: it is composed by an electromagnet which when an electric current flows on it, the piston in it draws back. So a little lever can push a mechanical part that opens the sliding blinds: when the current stops to flow into the coil of electromagnet the lever comes back in the original position and closes the blinds.

We drive the shutter with a square wave with a frequency of 1 Hz provided by a timer circuit: at this chopper frequency the responsivity of the sensor is max.

The coil of the shutter absorbs quite high current and it generates heat which can disturb the measure, so we use a little impeller in order to cool the sensor surrounding zone.

![Fig.1 The final prototype](image)

For the acquisition and the visualization of the sensor signal we used a PCI-6024E board (National Instruments) and LabVIEW (Laboratory Virtual Instruments Engineering Workbench, National Instruments) software.

In order to test our prototype we need a flow simulation: due to the complexity of this problem it’s difficult to implement fluidodynamic simulator in vitro which are reliable and refer to the clinical case for this scope.

For these reasons we focussed our attention to model a laminar flow into a flexible tube with dimension as possible as close to the first part of the left coronary artery one, and to control the temperature of the flow which flows into the pipe. The result, obviously, is far to simulate the coronary circulation but it’s indispensable to test the device and to evaluate the predicted theory.

The device that we used is constituted by a water pump, with a thermostat, which pushes the fluid at fixed temperature into a silicon tube with a diameter of 4 mm and a thickness of 1 mm.

As the silicon has low emissivity (0.3) rather than blood vessel, we used a copper hollow tube with the same dimension of the previous pipe. Copper, in fact, has an emissivity (0.98 if it’s painted matt-black) closer to thermal characteristics of human tissues: this material is often used to construct manikins in order to analyse the heat exchange during surgery hypothermia \([6]\).

**Results**

First of all we found the in/out characteristic of the sensor: we used the pump to vary the temperature of the water in the tube from 30 to 37 °C (step of temperature variation: 0.2 °C) and the LabVIEW program to visualize the voltage responsivity on PC monitor.

As we can note from Figure 2, the correlation between the responsivity of the sensor and the temperature of the fluid is very similar to linear trend.
The results refer to the final configuration with chopper on, after the calculation of peak by the peaks detector program. In the voltage responsivity we included even the offset voltage, depending by the FET polarization, that for the sensor we have used is 1 V.

Another test consisted in the measurement of the sensor responsivity after a flow interruption that simulates an artery ischemia: starting from a temperature of 37 °C we closed the tube for 5 minutes.

As shown in Figure 3, we measured a rapid voltage responsivity drop due to the temperature decreasing of the tube up to room temperature.

Final laboratory test consisted of the measurement of the responsivity after reperfusion (Figure 4): starting from empty tube condition (at room temperature) we switched on the flow with a temperature of 37 °C to evaluate the time of the sensor for reaching this temperature. As we can note, during early 10 seconds the sensor responsivity almost reached the value corresponding to the temperature set by the pump.

During a surgical operation of a little pig we tested the device on the carotid.

After 1 minute of base measurement we interrupted the blood flow in order to simulate an artery ischemia: after the occlusion the device voltage responsivity decreased gradually because the temperature of the vessel went down. The ischemia was hold for 2 minutes: in this time range the responsivity dropped of about 18%. Figure 5 shown the correlation between the device responsivity and time: it’s possible to note that the drop is quite linear.

During a surgical operation of a little pig we tested the device on the carotid.
Finally we examined the reperfusion of the vessel: we activated the blood flow in order to simulate a reperfusion of the vessel: it’s possible to note (see Figure 6) that the voltage responsivity, so the temperature, increased rapidly, in fact after about 1 second from the reperfusion the voltage returned to the initial value.

**Conclusions**

The present article describes the study of a low cost portable device for the detection of the blood temperature during a surgical operation for coronary bypass implantation.

The amplitude of the sensor output signal is proportional to the energy of infrared radiation emitted by the vessel, so each peak of this signal corresponds to the relative temperature of it. Using a thermostated water pump, we obtained a complete characterization of the device, in particular the relation between its responsivity and the temperature of the area of interest.

This paper describes an experimental study conducted according to a physical model, and in vivo measurements during surgical operation of a little pig.

**Acknowledgments**

The authors thank Mr. S. Melchionda for his assistance in prototype designing.

Particular thanks to Mr. F. Vivaldi (Interdepartmental Research Center “E. Piaggio”, Engineering Faculty, University of Pisa, Italy) for his useful help in the device building.

Special thanks to Luigi Taddei (C.N.R. Institute of Clinical Physiology, Pisa, Italy) for his help in the device in vivo testing.

**References**


