MONITORING OF THE HEART STATE DURING CARDIOSURGICAL INTERVENTIONS

A. Nowakowski*, J. Wtorek*, M. Kaczmarek*, K. Grzęda*, K. Kudlak*, J. Siebert**, B. Trzeciak**, W. Stojek***

* Gdansk University of Technology/Department of Biomedical Engineering, Gdansk, Poland
** Medical University of Gdansk/University Centre for Cardiology, Gdansk, Poland
*** University of Gdansk/Department of Animal Physiology, Gdansk, Poland

antowak@biomed.eti.pg.gda.pl

Abstract: Recent work concerning methodology of monitoring of the heart state during cardiosurgical interventions performed in animal experiments is presented. The aim of this study is preparation of handy and reliable tools applicable in real clinical environment for continuous inspection of interventions in open-heart surgical procedures. Our notice is concentrated on electrical and thermal inspection of the heart-state. Measurements are performed on pigs with the open chest typically during forced heart ischemia, evoked by clamping the left descending artery. Experiment results showing importance of such measurements are reported. Value of contact electrical impedance measurements (EI spectroscopy) and of non-contact IR-camera thermal observations (classical and active dynamic thermography) of the heart tissue in affected as well as unaffected regions of the heart muscle are discussed. Mutually complementary importance of both modalities is underlined.

Introduction

The aim of this work is to discuss problems of effective inspection of the state of the heart during cardio-surgical open chest interventions and to propose handy and effective tools for monitoring state of the heart muscle. We ask the question if there are any possibilities to minimise risk of such interventions. To answer this question we performed several experiments *in vitro* and *in vivo* on pigs. The main problems were in searching of proper procedures and tools for monitoring of the heart tissue properties as well as functionality of this organ. We concentrated on two techniques: non-contact infrared thermal imaging of the heart muscle and on contact measurements of its electrical activity represented also by electrical impedance. Properties and value of both modalities in this specific field of applications is discussed.

Thermal state of the heart is monitored by simple registration of IR radiation emitted by the observed surface of the heart while thermal properties of the heart muscle are calculated from active dynamic thermography (ADT) experiments based on external thermal (usually optical) excitation. We already have a long lasting experience in development of ADT for medical applications and in implementation of thermal IR-imaging in cardiosurgery [1, 2, 3, 4, 5].

In parallel, electrical activity of the heart (*ECG*) is under constant control and registration to react immediately in a case of any warning signs. This information is also used in the case of measurements to be synchronised with the heart action as thermal imaging of the moving structure may be affected by nor precise positioning of the captured images. To solve this problem optical camera may be also applied to register precisely position of the moving organ to allow corrections of the IR images.

Electrical impedance measurements are performed for the heart inspection for many years [6, 7, 8] and the high value of this method was already accepted for evaluation of transplants [9]. We are working in application of electrical impedance for many years having also some experience of using this technology in cardiosurgery, e.g. [10, 11]. In the experiments reported in this paper we are using typical electrodes for ECG and the four-pole electrode configuration for measurements of electrical impedance. Use of several shapes of electrodes and instruments for electrical impedance measurements are here discussed.

Based on *in vitro* or on *phantom* measurements, the first stage of this study was devoted to evaluation of instrumentation constructions. We searched for several solutions of electrode constructions and instrumentation for electrical impedance measurements. Also the question how to perform registration of thermal images, especially experiments using active dynamic thermography – heating or cooling of the heart muscle surface – is not decided, yet. Results of experiments using different approaches and instrumentation construction are here discussed. Practical observations are of the highest importance.

Materials and Methods

For i*n vivo* experiments on animals (performed according to all legal regulations and permission of the Local Ethics Commission for Experimentation on Animals at the Medical University of Gdansk, Poland) the pigs have been accepted for experiments due to the closest to human physiological and anatomical structure of the heart muscle and the circulatory system.

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The experiments were conducted on several young domestic pigs, each weighing approximately 25 kg. Anaesthesia and analgesia were obtained by the administration of ketamine (im), pentobarbital (iv) and fentanyl (iv) at doses of 20, 30-50 and 0.5–0.1mg/kg, respectively. The chest was open as it is shown in Fig.1 to have full access to the heart muscle. Intubation was applied during all experiment time. To evoke the heart muscle ischaemia the left descending artety LAD was clamped, totally blocking delivery of the blood.

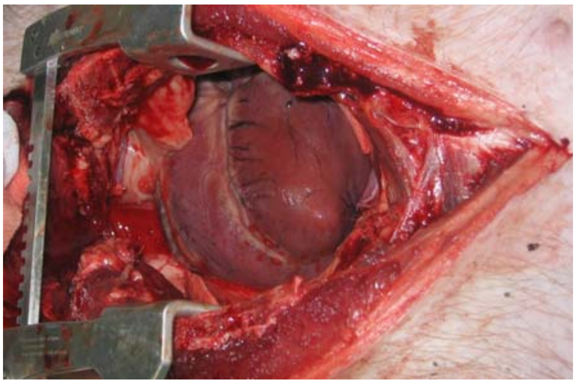

Figure 1: Exposition of a pig heart before

Optimised solutions of instrumentation have been analysed during such experiments as: evoked heart stroke, CABG, OP CABG procedures and some other. Non-invasive measurements have been also already applied to clinical cases.

Electroimpedance Instrumentation

One of important problems was to get the highest possible resolution of electrical measurement, as the answer of the heart muscle to electrical stimulation may be non-linear. We expected that such measurement may be holding important diagnostic information as the level of non-linearity may be carrying extra knowledge of the heart tissue properties. The circuit based on high performance ADC converters, as it is shown in Fig.2 was applied. At this stage the experiments were supported by advanced simulation of the heart muscle electrical properties. The problem still is not fully solved, as the level of non-linear signals is very low. The results of measurements with 16-bit resolution are encouraging especially at low measurement frequencies.

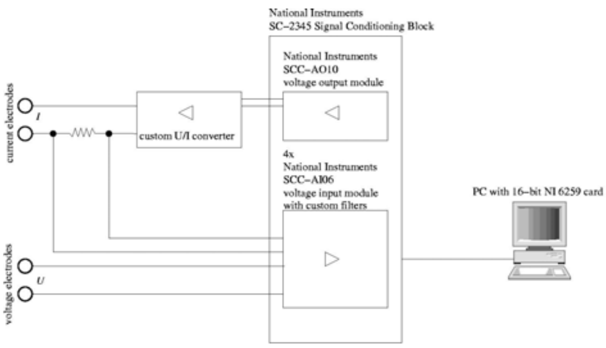

Figure 2: Block diagram of the measurement circuit based on National Instrument PCI-6259 card

For classical electroimpedance measurements the circuit shown in Fig.3 was applied using special arrangement of measurement electrodes integrated with mechanical holder developed for stabilisation of the srface of the working heart. The Solartron Impedance Analyser 1260 with developed front-end circuits allows spectral measurements of electrical impedance in a broad range of frequencies.

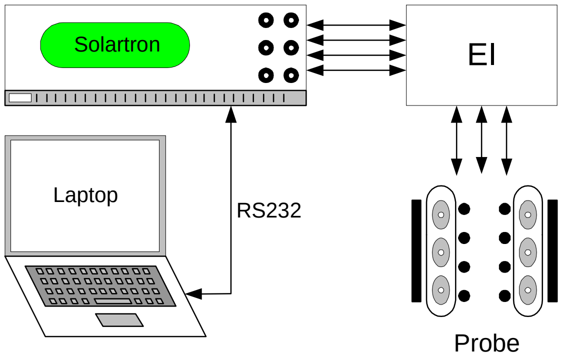

Figure 3: Experimental stand, EI- electronic interface

The arrangement of electrodesis combined with the mechanical stabiliser with sucking holding arms, typically applied in OP CABG interventions, is shown in Fig.4.

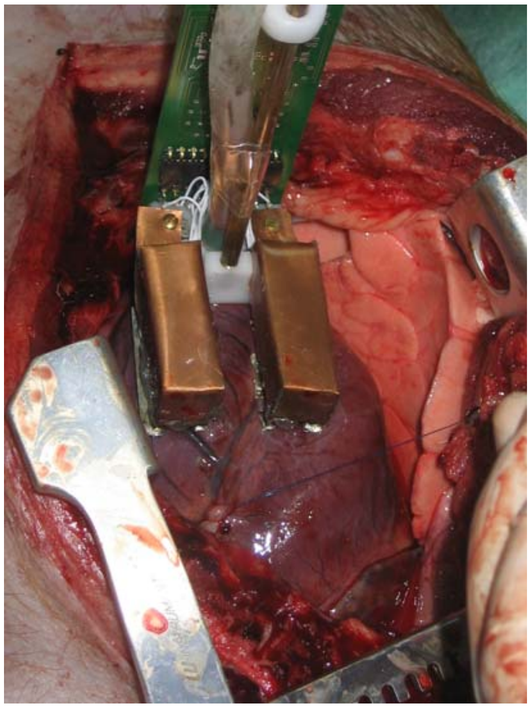

Figure 4: Mechanical stabiliser with electroimpedance electrodes applied to the heart

The four-pole configuration of electrodes is typically applied as it is shown in Fig.5. Current electrodes are placed at the outer part of the sucking arms. In our experimental arrangement several voltage electrodes are applied allowing measurements of electrical field distribution.

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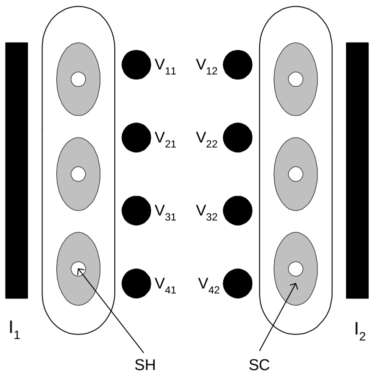

Figure 5: A schematic diagram (bottom view) of the probe combined with sucking holder, I and V stand for current and voltage electrodes respectively while SH marks sucking holes and SC sucking cups

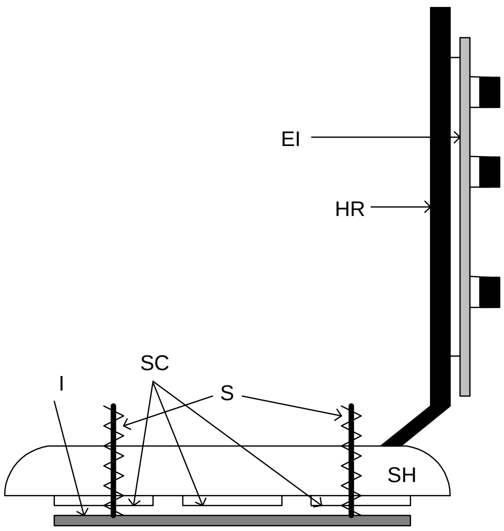

Figure 6: Lateral view of the measuring probe, EI – electronic interface, HR – holding rod, SH – sucking holder, I – current electrode, SC – sucking caps, S – spring enabeling the current electrode to be connected with a prescribed force to the heart muscle; similar approach have been used to fix voltage (circular) electrodes

IR Imaging Instrumentation

The concept of *Infrared Non-Destructive Testing* (*IR*/*NDT*) is known in industry for several years [12]. *ADT*, which is a new modality in medical applications, may be regarded as one of the advanced versions of *IR/NDT*. Analysis of heat transfer enables thermo-physical material properties, such as thermal diffusivity or conductivity, to be quantified and the subsurface structure to be determined.

The general concept of measurements performed in *ADT* is shown in Fig.7a. First, the steady state temperature distribution on the tested surface is recorded using an IR camera. Next, external thermal excitation (heating or cooling) is applied, followed by measurements of temperature transients on the tested surface. Typically, a set of halogen lamps may be applied as the thermal heating excitation source. We have tested also cooling using cold air forced flow

To assure high quality of thermal images the registration should be synchronised with the heart action, as it is shown in Fig.7b. Thermal transients at a specific pixel position are illustrated in Fig.7C. Single pulse of heating energy is generated forcing rise of the surface temperature. When the heating energy is switched off the temperature is falling down due to natural heat flows dependent on internal but also external boundary conditions.

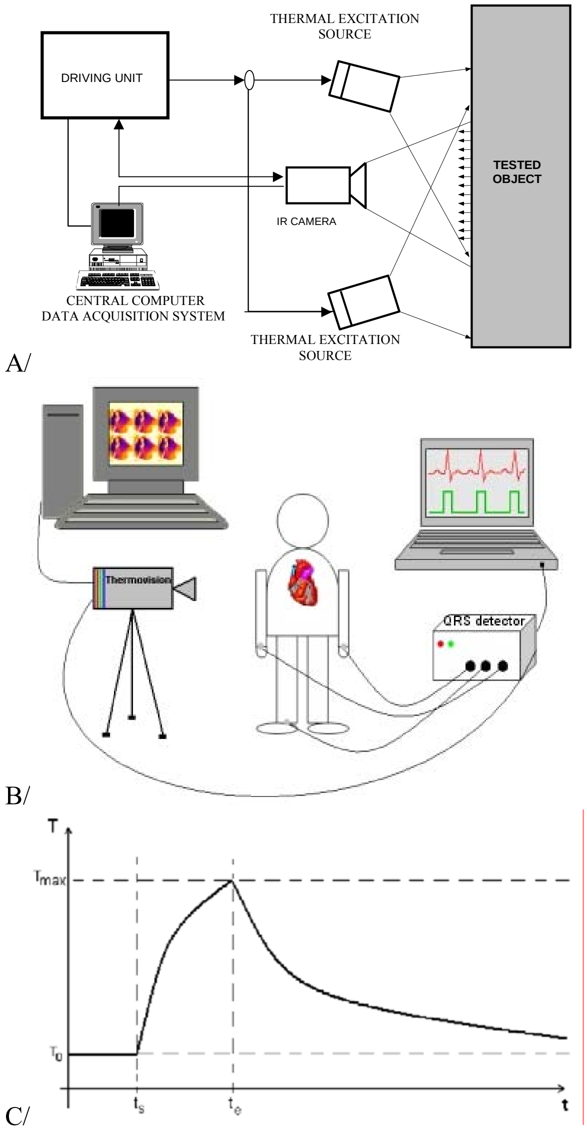

Figure 7: A/ Schematic diagram of the ADT instrumentation. The IR camera is synchronised with an excitation source. In the experiment described here this was a set of halogen lamps and an air cooling system. Surface temperature of the tested object is recorded at a speed of 30 frames/second. Changes in this temperature are caused by the external source and are dependent on the internal state of the heart muscle. B/ Registration of thermal transients may be synchronised with the heart mechanical action to avoid movements of the heart muscle. C/ Temperature trace for a given pixel during ADT investigation after single pulse excitation (here rise of temperature) and natural cooling phase, when temperature is recorded

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Fig.7c shows the tracing of temperature in a specific pixel position *x-y,* taken after a thermal pulse excitation. In ADT experiment described measurements of temperature are performed only during the recovery phase (in this case the cooling phase following the heating). Thermal transients are described by exponential functions. For one directional heat flow the simplest description of surface temperature changes may be given for the cooling phase by:

$$T(t)=T_0+\Delta T\ [exp(-t/\tau)],$$

where $T(t)$ is the pixel temperature T in time t; T_0 is the temperature before excitation; ΔT is the temperature rise due to excitation. The value of the thermal time constant $\boldsymbol{\tau}$ depends on different existing mechanisms of heat flow and is strongly correlated to the physical structure of the heart muscle, therefore, the tested tissue can be quantitatively assessed by means of the thermal time constant **(τ).**

Each pixel in the recorded series of thermal images shows the temperature changes at a specific point on the surface tested. Single excitation and registration of transient temperatures at the position *x-y* allows identification of the structure "*in depth"* on the basis of the equivalent thermal model and for all pixels, resulting in a 3D image of the object tested.

In our case the temperature of each pixel is recorded to calculate the thermal time constant specific to each pixel (correlated with the blood flow). The parametric image of the time constants enables the tested surface to be visualised, owing to the high degree of correlation with the depth of the affected tissue.

Additionally visible light digital camera may be applied for continuous observation of surgical interventions. Visual and IR images may be matched, as it is shown in Fig.8. Such procedure may be important for necessary precise localisation of the heart muscle position. Usually external markers are applied for holding the picture stable in time.

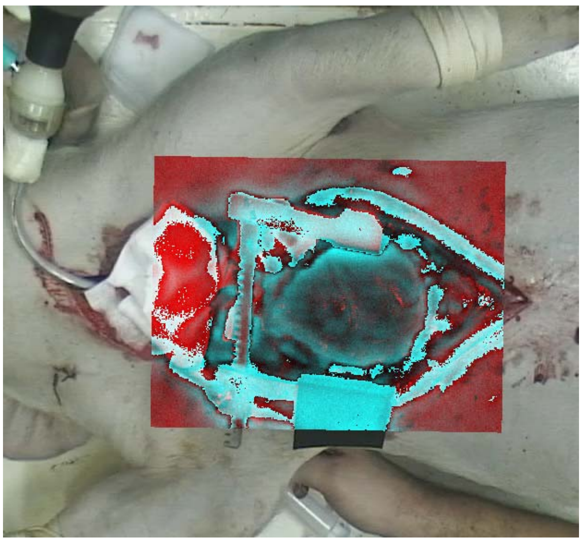

Figure 8: Co-registration of thermal and visual images

Results

The results of the research are based on comparison of the value of applied monitoring tools and are followed also by practical cases in clinics using:

A/ analysis of electrical signals (ECG);

B/ electroimpedance as a figure of merit in description of tissue parameters;

C/ absolute temperature and temperature transients during the surgical intervention;

D/ thermal properties of the heart muscle, measured in active dynamic thermography experiments. This case will be illustrated for both – heating and cooling - for optical excitation and forced flow of air.

According to electrical non-linearity of the heart muscle even the theory clearly shows this phenomenon the achievable accuracy of measurements strongly masks this effect. Therefore, having significant theoretical background, in practice we still failed to see all we expected. This part of the work still is under investigation and we hope to get more results in experiments to be performed in the nearest future.

As an example of measurements performed using the acquisition system shown in Fig.2 typical measurement results are presented in Fig.9.

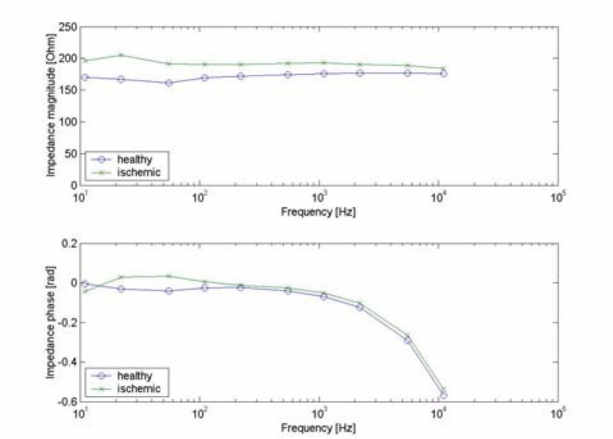

Figure 9: Impedance characteristics recorded before ("healthy") and 10 minutes ("ischemic") after LAD occlusion

Use of instrumentation shown in Fig.4 is illustrated by exemplary measurement results in Fig.10. Generally, the arrangement of electrodes integrated with the mechanical stabiliser of the heart for OP CABG interventions allows continuos in time inspection of the electrical impedance and even measurement of impedance distribution for the multi-electrode solution. Any changes of this impedance may be automatically triggering a warning signal important for the operator.

Several, important observations are possible from electroimpedance measurements, which are also visible from IR-imaging. One is the clear evidence of devastating influence of ischemia, which is affecting structure of the heart muscle as it is shown in Fig.10. This observation is confirmed by IR-thermal observation as well as by ADT experiment.

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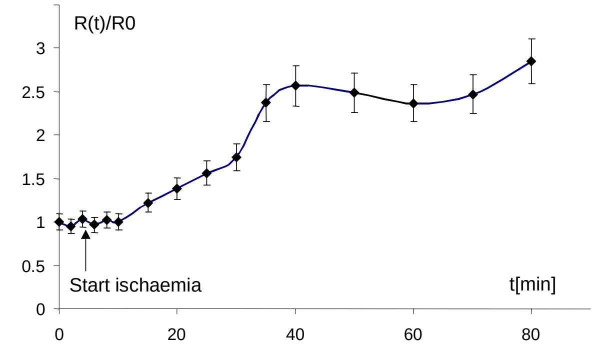


Figure 10: Resistivity measured at 5 kHz for a set of electrodes (Fig.5 - I_1, I_2, V_{21}, V_{22}) and the mechanical stabiliser placed as in Fig.4 close to the centre of the affected vascularisation region of the heart muscle

Some results of IR-thermal imaging showing functionality of the heart muscle are shown in Fig.11.

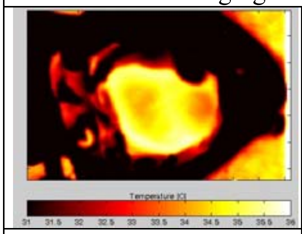
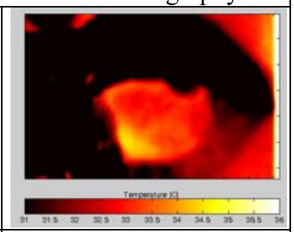
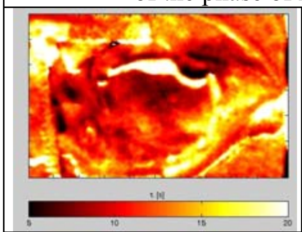
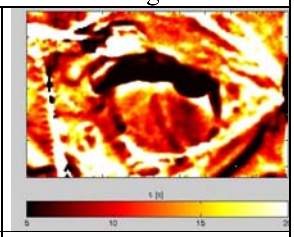
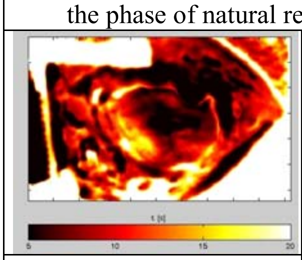
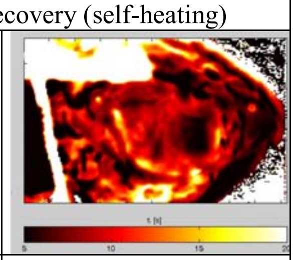
Before blood arrest by clamping LAD	30 minutes after the blood arrest
IR-thermal imaging – classical thermography	
	
a/	b/
ADT experiments – parametric images of τ –thermal time constant of the heart muscle tissue	
Optical – halogen pulse excitation (heating) lasting 15 seconds and followed by 60 second registration of the phase of natural cooling	
	
c/	d/
Cooling 30 seconds by forced air flow of the temperature 5^0 C; registration during 90 seconds at the phase of natural recovery (self-heating)	
	
e/	f/

Figure 11: Thermal study results of the heart muscle before and 30 minutes after evoked ischemia – a/ & b/ temperature distribution IR-images; c/ & d/ ADT parametric images for optical excitation (heating) and e/ & f/ ADT for air cooling respectively before and after evoked ischemia

The results of ADT experiments - heating with optical excitation, c & d, and cooling by forced air flow, e & f, are of the same character and give information of the tissue properties. After 30 minutes of clamping LAD the structure of the tissue is already strongly affected.

Conclusions

Basic conclusions show importance of both modalities, electroimpedance and thermal visualisation, which in the case of cardiosurgery interventions are complementary. The same properties of the heart muscle may be monitored using proposed thermal and electrical instrumentation. The main advantage of IR thermal imaging is complex picture of all interesting regions at once, while electrical impedance shows mainly local properties.

Both, functional and structural electrical and thermal properties of the heart muscle are affected by ischemia. This is not only due to limited vascularisation but also by visible in histopathology investigation changes in cell structures in the affected regions.

Visualisation of temperature distribution at the surface of the heart muscle is less invasive than electroimpedance measurements being a fully non-contact procedure. The only condition for measurements in this case is visual accessibility to the tested region, what is possible not all the time but in practice is not disturbing surgical interventions.

The set of ADT parametric images gives rather structural information of the tested tissue. Properties of tissue are dependent on blood flow and physical structure, which is devastated after long lasting processes of ischemia. Blood arrest has damaging influence on the structure of cells what may be easy evidenced by histopathology. Therefore the ADT images are differentiating tissues already affected but are not sensitive to short deficits in blood flow.

Medical diagnostic importance of such monitoring is of high value. All phases of the surgery procedure are under direct and prompt control.

The main advantage of electroimpedance instrumentation is low cost of instrumentation. Also recent advances of IR imaging are promising as the cost of such instrumentation is constantly falling down.

Acknowledgements

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