QIRT 2018
10.21611/qirt.2018.012
14th Quantitative InfraRed Thermography Conference

Simulation of skin properties by a low pass filter for thermal waves: application to thermography-based real-time blood flow imaging

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Abstract
We propose a new concept: the human skin as a low pass filter for thermal waves. Using this theoretical approach allows to convert the signal of temperature oscillations into skin blood flow signal at the surface of limbs in real-time. We have demonstrated an adequacy of the model to the object under study during cold induced vasodilatation, deep inspiratory gasp and post-occlusion reactive hyperemia test. Using the inverse high pass filter (HPF) allows reconstructing of skin blood flow from temperature in real-time. Connection of the electrical schema of HPF to a temperature measurement device can expand its capability and allow estimating the waveform of blood flow oscillations.

1. Introduction

Development of technique for skin blood flow imaging have a high practical importance in the many fields of medicine, for example, in a monitoring of skin flap engraftment and treatment of burns, chilblains, as well as for observation of postoperative period after transplantation and replantation of fingers and toes [1]. Standard thermography techniques allow visualizing the distribution of temperature which is indirectly related to hemodynamics. In this case, the possibility of converting dynamic thermograms into a two-dimensional distribution of skin blood flow is an attractive prospect, since thermography provides high spatial and temporal resolution, as well as a wider field of view compared with laser Doppler or speckle-contrast imaging techniques. The waveforms of skin temperature and blood flow oscillations do not match as shows experimental measurements. Earlier we have established spectral amplitude and phase relationships between skin temperature and blood flow oscillations [2]. Analysis of the relationships shows a possibility of simulation of thermal properties of skin by a low-pass filter. The low pass filtering effect of the finger was noted earlier by [3], but conversion of temperature signal into blood flow was performed on the basis of phenomenological approach without assumptions about physical properties of skin. Here we use experimentally established relations between temperature and blood flow spectral components investigated in [2], and theoretical model which explains low pass filtering properties of the skin. At present time thermography-based blood flow imaging realized in post processing mode by using Spectral Filtering Approach [4]. The **aim of this research** was a simulation of thermal properties of skin via low pass filter, and using of this technique for the real-time skin blood flow imaging in limbs.

2. Methodology

2.1 Background

It is well–known that volumetric blood flow in blood vessels of fingers is modulated by different physiological mechanisms of variation in vascular tone (cardiac, respiratory, myogenic, neurogenic, endothelial and perhaps others), wherein each mechanism impacts within its frequency interval, thereby the blood flow oscillations have a complex spectral distribution [5]. The conduction of heat from blood to skin surface involves two components: the heat conduction from blood to biological tissue and the propagation of heat perturbation through the biological tissue to the skin. The blood flow oscillations can be considered as the source of proportional temperature perturbations that propagates within skin from a depth of about 1–2 mm to the skin surface and are called as thermal waves. The velocity of propagation and amplitude attenuation of thermal waves depend on the medium through which it propagates. The wavelet–analysis of experimentally measured spectral components of temperature oscillations and blood flow showed that the attenuation of temperature spectral components increases whereas delay time decreases with increasing of square root of the frequency [2]. Applying spectral filtering approach it is possible to convert the dynamic infrared thermogram of skin into sequences of 2-D blood flow images [4]. Blood flow videos are available at http://livetir.com/blood-flow-videos.php.

2.2 Analogy between the electrical properties of the filter and the thermal properties of the skin

Thermal waves originate in the deep of the skin and then travel towards the skin surface (Figure 1, left panel). Since, an attenuation of waves is increases with increasing of frequency, the skin, as a medium for propagation, have properties similar to the electrical low pass filter (LPF) (Figure 1, right panel). It is common knowledge that the electrical filter describes by amplitude and phase responses. Consequently, simulation of skin thermal properties reduces to optimal selection of analytical expressions for the above responses.

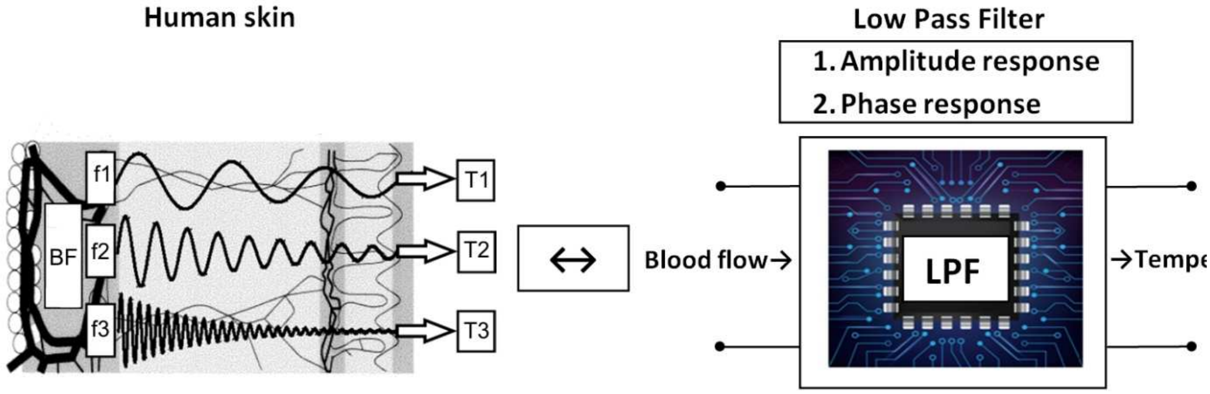

Fig. 1. *Analogues between thermal properties of human skin and electrical properties of low pass filter (LPF) (BF- blood flow oscillations; f1,f2,f3 – different frequencies of thermal waves provoked by the blood flow, T1, T2, T3 – spectral components of temperature signal at the skin surface)*

2.3 Analytical description

In the analytical form properties of the filter that simulates skin properties can be written as follows:

$$H_{Skin}(f, z) = Amp_{LPF}(f, z) \cdot e^{j \cdot Phase_{LPF}(f, z)}, \quad (1)$$

$$AMP_{LPF}(f, z) = \exp\left(-z \cdot \sqrt{\frac{\pi f}{\chi}}\right), \quad (2)$$

$$Phase_{LPF}(f, z) = z \cdot \sqrt{\frac{\pi f}{\chi}}, \quad (3)$$

where H_{skin} – is the transfer function of the low pass filter that simulates the skin properties, $Amp_{LPF}(f, z)$ – is the amplitude response of the low pass filter, $Phase_{LPF}(f, z)$ – is the phase response of the low pass filter; f– is the frequency of oscillations (Hz), j – is an imaginary unit, $\chi=k/(c \cdot \rho)$ –is the thermal diffusivity of skin (m^2/s) . Knowing the spectral function of H_{Skin} one can find the impulse response function $Imp_{LPF}(t)$. The convolution of blood flow signal $BF(t)$ (measured by photoplethysmography or laser Doppler flowmetry, for example) with the impulse response function allows to calculate the temperature $T(t)$ at the surface of the skin:

$$T(t) = BF(t) \otimes Imp_{LPF}(t) = \int_0^t BF(\tau) \cdot Imp_{LPF}(t-\tau) \cdot d\tau, \quad (4)$$

$$BF(t) = T(t) \otimes Imp_{HPF}(t) = \int_0^t T(\tau) \cdot Imp_{HPF}(t-\tau) \cdot d\tau, \quad (5)$$

where $\otimes$ - is the convolution operator, τ – is the parameter of integration. The impulse function for the high pass filter Imp_{HPF} can be calculated from the inverse transfer function $H_{Skin}^{-1}(f, z)= H_{Skin}(f,-z)$.

2.3 Algorithm for the real-time transformation of temperature signal into blood flow

As a result an algorithm for the real-time blood flow imaging (Inverse transform) in the each pixel of the thermogram looks like the following sequence of operations: live thermogram recording → getting 2-dimensional temperature values → calculation of the blood flow value using the impulse function Imp_{HPF} in the expression (5) in the each pixel of the thermogram→ using pseudo palette for a coloring of blood flow images (see table 1).

Table 1. *The schema of transformation of blood flow signal into temperature, and vice versa*

Direct transform:	Blood flow →	**Low Pass Filter**	→Temperature	Expression (4)
Inverse transform:	Temperature →	**High Pass Filter**	→Blood flow	Expression (5)

3. Results and discussion

3.1 Examples of simulation

3.1.1 Cold-induced vasodilatation (CIVD) of finger vessels

When a human finger is immersed in a cold water, i.e., temperature below 15°C, the skin temperature falls and remains low for 5–10 min, but then increases abruptly. It was shown by Bergersen et al. [6] that increasing of skin temperature during cold-induced vasodilation are caused by relaxation of the smooth muscle cells of the arteriovenous anastomoses. Vasodilations and vasoconstrictions during the cold challenge can be simulated by triangles sequence. Figure 2 shows examples of transformation of the blood flow signal into temperature.

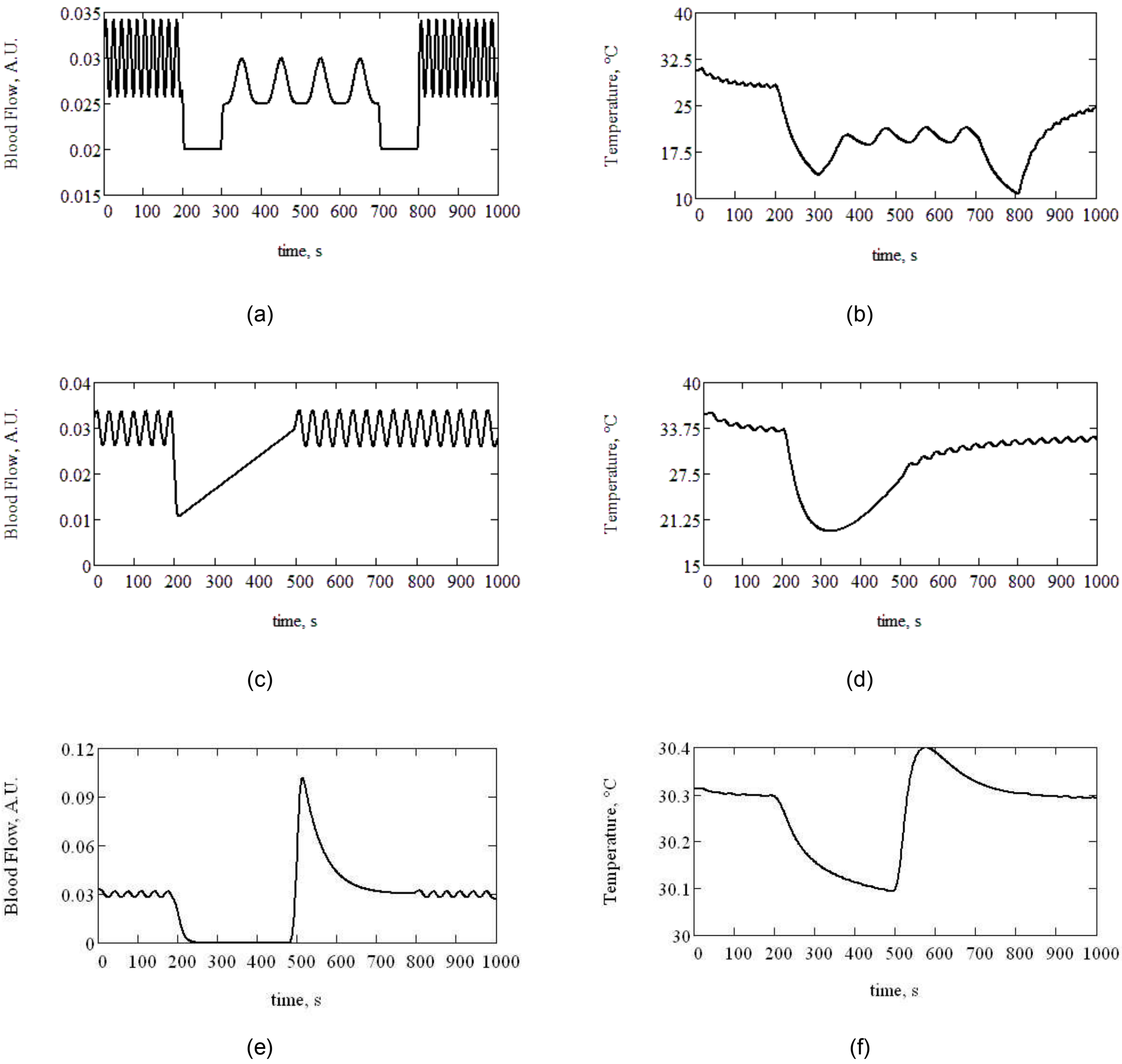

Fig. 2. *Examples of transformation of model input blood flow signals into temperature: a) Blood flow during cold-induced vasodilatation; b) Temperature output signal during cold-induced vasodilatation; c) Blood flow during inspiratory gasp challenge; d) Temperature output signal during inspiratory gasp challenge; e) Blood flow during post occlusion reactive hyperemia (PORH) test; f) Temperature output signal during PORH test*

CIVD reaction simulates by a series of almost triangle waveforms corresponding to vasodilatations and vasoconstrictions. Temperature dynamics at the surface of skin looks like sine waves (figure 2 b) because of suppression of high frequency components of blood flow by the human skin. The results of simulation of CIVD are very close to experiment data demonstrated by Bergersen et al. [6].

3.1.2 Deep inspiratory gasp

Deep inspiratory gasp is a reaction of vasoconstriction type (figure 2 c) which occurs when you deeply and sharply inhale. The reaction explains by stretching of vena cava during breath moving of diaphragm and thorax. The simulated temperature reaction on deep inspiratory gasp (figure 2 d) is close to that described by Allen et al. [7].

3.1.3 Post occlusion reactive hyperemia test (PORH)

PORH test provokes a combination of vasoconstriction and vasodilatation reactions. During the arrest of blood flow (figure 2e) a vasoconstriction is occurs, a heat does not deliver to a skin by a blood, and skin temperature falls (figure 2 f). Opening of blood flow leads to increasing of shear stress applying to vessels wall and vasodilatation leading to reactive hyperemia and increasing of skin temperature (figure 2 f). The waveform of temperature reaction, in general, coincides with experimental results, for example, presented by Akhtar et al. [8].

3.2. The value of the model for practice

Described model shows a theoretical possibility for the design of high pass filter converting temperature into blood flow in real-time. Connection of the electrical schema of high pass filter to a temperature measurement device can expand its capability and allow estimating the waveform of low-frequency blood flow oscillations. Application of the algorithm in the each pixel of the dynamic thermogram opens prospects for the 2-D thermography-based skin blood flow imaging. Among the potential applications of the model are a non–contact monitoring of blood supply during skin engraftment and a treatment of burns and others.

4.Conclusions

As a result we have proposed the model based on simulation of thermal properties of skin by a low pass filter. Using the inverse high pass filter allows reconstructing of skin blood flow from temperature in real-time. Here we have demonstrated an adequacy of the model to the object under study during cold induced vasodilatation, deep inspiratory gasp and post-occlusion reactive hyperemia test. The simulation of skin by a low pass filter for thermal waves and application the algorithm of real-time conversion of temperature into blood flow will allow using a thermal imaging camera as a tool for blood flow imaging in limbs.

ACKNOWLEDGMENTS

The experimental study of hemodynamic response of limbs to occlusion was funded by the Russian Science Foundation (project № 17-75-10130); development of the algorithm of real-time convertation of temperature into blood flow was supported by President of the Russian Federation Council for the support of young Russian scientists – PhD (grant No. MK-997.2017.8).

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