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Journal of Theoretical Biology 238 (2006) 575–587

Journal of Theoretical Biology

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A new method to model change in cutaneous blood flow due to mechanical skin irritation
Part I: Comparison between experimental and numerical data

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Received 10 January 2005; received in revised form 14 March 2005; accepted 10 June 2005
Available online 2 August 2005

Abstract

Mechanical skin irritation creates vasodilation. Vasodilation of vascular networks induces increase in blood volume and blood velocity. Both can be measured by Laser Doppler Velocimetry. We propose in this article a method permitting comparison between experimental and numerical results. Experimental data was obtained by Laser Doppler Velocimetry. Numerical results were obtained by a continuous model of the vascular network. The model consists of three layers. First and last layer are described by anisotropic and heterogeneous porous media. They represent the irrigation and the drainage of the vascular system. The intermediate layer is described by a lumped parameter model that does not permit horizontal fluxes. All vessels are compliant. The permeabilities depend on the volumes of the specific layer. Skin irritation is modeled by a change in compliance of small arterial blood vessels.

The comparison between experimental and numerical data is based on the model proposed by Bonner and Nossal [1981. Model for laser Doppler measurements of blood flow. Appl. Opt. 20, 2097–2107]. The model describes the Doppler frequency spectrum $S(\omega)$ as a function of the optical phenomena creating the frequency shift. The comparison is based on the model of the first moment $M_1 \sim \int \omega S(\omega)\,d\omega$. The variables of the first moment can be determined by results of the numerical model.

We have shown, that it exists a linear relation between the change in compliance and the following increase in first moment. Using this linear relation experimental and numerical data can be compared.

Keywords: Porous media; Three layer model; Laser Doppler Velocimetry; Comparison

1. Introduction

The reaction of the cutaneous microcirculation to mechanical skin irritation (for example, a light scratch with a needle) has already been described by Lewis (1927). Three different reactions have been distinguished. The first reaction, called red reaction, describes the vasodilation on the line of stroke. It is due to histamine release from mast cells situated in the damaged tissue. The second reaction is known by the name nervous reaction or flare. Scratching skin stimulates pain receptors (free nerve endings) situated in the superficial dermis. Nervous signals induce neuropeptide release in the surrounding tissue of the line of stroke.

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0022-5193/$ - see front matter
doi:10.1016/j.jtbi.2005.06.023

Neuropeptides are vasodilators. They create spreading of the zone of vasodilation. Vasodilation of the red reaction takes place nearly immediately after the stroke. The nervous reaction shows a delay of 20–30 s (Schmidt and Thews, 1995). This delay is not due to the traveling time of nervous signals, but to the reaction time of neuropeptides (Weidner et al., 2000). Both, histamine and neuropeptides create vasodilation by decreasing vascular smooth muscle contraction state and hence vessel compliance. The third reaction describes the formation of an edema, that occurs if the stroke is sufficiently strong.

The spreading of the zone of vasodilation due to a light scratch is shown in Fig. 1. The pictures are taken at an interval of 26 s using a Laser Doppler Imager (PIM II, Perimed, Sweden). Each picture corresponds to an area of 2 cm $\times$ 2 cm (20 $\times$ 20 measuring points). The baseline flow was measured three times. Then, the scratch was applied after 76 s. The results show that the vasodilation due to the red reaction reaches its maximum after the onset of the nervous reaction. A clear distinction between the red and the nervous reaction is not possible.

The degree of vasodilation depends on the intensity of the stroke, but also on the skin type of the subject. The direct relation between the intensity of stroke and the change in contraction state of smooth muscles is not known. Hence, in order to model entirely the first and the second reaction of mechanical skin irritation it is first of all necessary to establish a method permitting comparison between experimental (change in blood flow measured by Laser Doppler Velocimetry) and numerical data (change in blood flow modeled by a porous media model of the vascular network proposed by Bauer et al. (2005)). Afterwards, an irritation law has to be identified. The law describes the change in smooth muscle contraction state as a function of the intensity of the stoke, the time and the distance to the line of stroke.

Laser Doppler Velocimetry is based on the frequency shift of light scattered by mobile particles. If multiple scattering takes place, the resulting signal is a frequency spectrum and not only a single frequency. Bonner and Nossal (1981) propose a model of the frequency spectrum. The model takes into account all optical phenomena that occur when light enters the skin until it reaches the photodetector. The model will be described below.

Blood flow in tissue can be considered as flow through porous media. Already Huyghe et al. (1989a, b), Vankan et al. (1996, 1997a–c, 1998) and Van Donkelaar et al. (2001) described muscle circulation by hierarchically arranged porous media. The model we proposed before consists of three layers. The first layer (irrigation) and last layer (drainage) are described by two-dimensional horizontal porous media. The first layer simulates the behavior of arteries and large arterioles. The last layer stands for veins and large venula. The intermediate layer models the microcirculation (arterioles, capillaries and venula). It consists of a lumped parameter model that does not permit horizontal fluxes. The model takes into account vascular network structure by applying anisotropy and heterogeneity to the porous media of the first and last layer. All vessels are compliant. Hence, change in smooth muscle contraction state is simulated by a

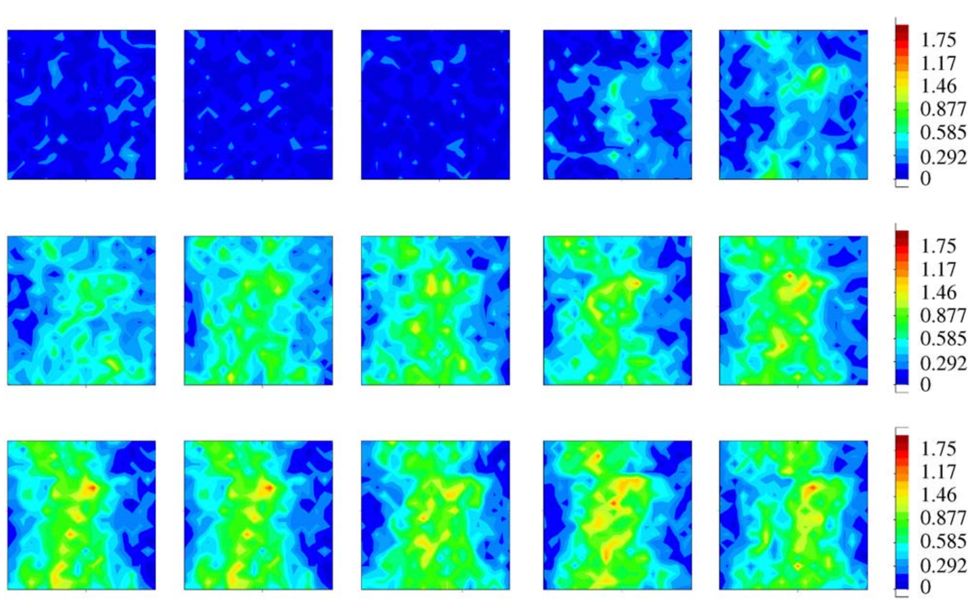

Fig. 1. Change in blood volume due to a scratch [arbitrary perfusion units (V)]. Blood flow is measured using a Laser Doppler Imager (PIM II, Perimed, Sweden). Each picture corresponds to an area of 2 $\times$ 2 cm (20 $\times$ 20 measuring points). Pictures were taken at an interval of 26 s. Baselineflow was measured three times. The scratch was applied after 78 s.