A Thermodynamic Model for Thermographic Analysis of Tissue Perfusion and Its Regulation

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• Dynamic infrared thermography is a very sensitive tool for the analysis of perfusion of superficial tissue and its thermoregulation. A thermodynamic model based on the local heat balance of tissue allows analysis of thermogram sequences recorded during rewarming of tissue after a carefully controlled cooling procedure. Physiologic parameters are derived from this model that are a measure of local blood flow and are characteristic of its regulation. The parameters are used as a quantitative and therefore objective basis for the classification of the severity of certain diseases and for monitoring therapy.

By use of these parameters in a pilot study with 19 volunteers, the perfusion of the labial gingiva and mucosa was shown to be considerably lower in juvenile patients with destructive periodontal disease. Furthermore, significant differences were demonstrated between the thermoregulatory behavior of tissue in a group of healthy volunteers and that of tissue in patients with vasospastic diseases.

Introduction

Local heat balance of tissue is determined mainly by tissue perfusion and its thermoregulation and by heat exchange with the environment.[1–4] Dynamic infrared thermography is a very sensitive tool for analysis of the perfusion of superficial tissue and its thermoregulation.[1,5–7] Microcomputer-assisted thermography systems allow acquisition of sequences of thermograms that depict the rewarming behavior of tissue after a provoked cooling procedure with a very high spatial, thermal, and temporal resolution.[8–10] However, analysis of the extensive information contained in a time series of thermograms and drawing objective conclusions from the analysis present a problem.

This paper presents a physical and physiological model that allows detailed analysis of dynamic thermogram sequences. Using the model, extensive information contained in the thermogram sequences can be reduced to a few parameters. These parameters are sensitive to tissue perfusion and its regulation, and can be utilized for a quantitative description of the thermoregulatory behavior of tissue.

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The model was applied in two clinical studies. The first study demonstrated that juvenile patients with destructive periodontal disease show reduced perfusion of the labial gingiva in comparison to healthy volunteers.[6] The second study showed that the thermoregulatory behavior of the extremities in patients with vasospastic diseases differs strongly from that of healthy individuals. The model also allowed these effects to be quantified; the results were used as a quantitative and therefore objective basis for classification of the severity of the disease and monitoring the effects of therapy.

Thermodynamic Model

The quantitative analysis of thermographic sequences depicting rewarming of the skin surface after a provoked cooling procedure is based on a physiological heat-balance model.[1,2] The change, δQ, in the heat content of a tissue element is determined by

$$\delta Q = \delta Q_{env} + \delta Q_{cond} + \delta Q_{perf} + \delta Q_{metab} \qquad (1)$$

The terms on the right-hand side of the equation represent: the heat transfer to the surrounding environment by radiation and convection (δQ_{env}); the heat transfer to the neighboring tissue by conduction (δQ_{cond}); the heat transfer to the circulatory system as the result of the perfusion (δQ_{perf}); and the heat produced by a metabolic process (δQ_{metab}).

Rewarming Behavior with Normal Thermoregulation and a Normal Rate of Blood Flow

If a normal rate of blood flow is maintained during the rewarming period, detailed studies show that heat transfer caused by blood circulation (δQ_{perf}) has the most significant effect on the tissue heat balance. This effect can be thermographically confirmed by measurements on human extremities with normal and with highly reduced blood flow. The other factors of the equation can be ignored. Applying the laws of thermodynamics to the remainder of the heat-balance equation, the behavior over time of the temperature, T, during the tissue rewarming phase can be described by a first-order differential equation

$$\frac{dT}{dt} = -k(T) \times (T - T_R) \qquad (2)$$