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Multi-scale modelling of heat and mass transfer in tissues and cells during cryopreservation including interval methods

PhD dissertation

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Abstract

This thesis is devoted to large-scale modelling of the coupled phenomena that occur during cryopreservation. This is a process that involves slowing down the activity of biological material by lowering the temperature below physiological temperature and then restoring the function of the cryopreserved tissues or cells, while preserving their basic vital activities. In order to avoid the negative effects of the process, chemical compounds called cryoprotectants and regulation of the cooling rate are used. This paper presents examples of cryopreservation methods such as slow freezing, vitrification and the “liquidus tracking” protocol. Transport phenomena such as heat transfer with crystallisation, mass transfer in the context of mass diffusion and fluid flow, and osmotic transport are also presented. The work includes examples of numerical simulations of individual transport phenomena. Heat transfer described by the Fourier equation or the Pennes equation was considered. Issues related to phase changes and the crystallisation of ice crystals, in which the degree of crystallisation was estimated using the non-isothermal Boutron-Mehl kinetic equation, were also considered. The work also investigated mass transfer coupled to the thermal problem. Using the convection-diffusion equation or Fick's second law in the case of neglecting advection, the problem of diffusion of molecules from the bath solution to the extracellular matrix solution was analysed. The paper also includes a description of the osmotic transport phenomenon using a two-parameter model to estimate the change in cell volume induced by the exchange of water and cryoprotectant molecules between the extracellular and intracellular solutions. The numerical model appearing in this paper is based on the finite difference method supplemented by interval and fuzzy arithmetic, in which the concept of α-cuts was used. In the mathematical model, fuzzy and interval numbers were introduced in place of deterministic parameters, taking into account their imprecision. Algorithms and original computer programmes were developed in the Embarcadero Delphi 10.4 Community Edition environment.