Postoperative evaluation of tumor based on label-free acoustic separation of circulating tumor cells by microstreaming

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Numerical simulations

Herein, bold and plain fonts are used to represent vectors and scalars, respectively. The symbols ∂_t was used for the partial derivatives of a given function $F(t)$.

$$\partial_t F \equiv \partial F/\partial t \tag{1}$$

In this study, we assumed the fluid is homogeneous and isotropic. The fluid response can be investigate by the compressible Navier–Stokes equations,

$$p = p(\rho) \tag{2}$$

$$\partial_t \rho = -\nabla \cdot (\rho v) \tag{3}$$

$$\partial_t(\rho v) = -\nabla p - \rho(v \cdot \nabla)v + (\zeta + 1/3\eta)\cdot\nabla\nabla\cdot v + \eta\nabla^2 v \tag{4}$$

where ρ, v, p, ζ, and η denote the mass density, velocity, pressure, bulk viscosity, and shear viscosity of the fluid, respectively. Due to the thermal diffusion length in liquids is much smaller than the momentum diffusion length, the isothermal case can be studied for simplicity without the heat transfer equation consideration.

If the oscillation amplitude is small enough, the induced fluidic response can be expressed by a perturbation expansion, and the fields of the fluid density, pressure, and velocity, were expanded as follows [1],

$$\begin{aligned} \rho &= \rho_0 + \varepsilon\rho_1 + \varepsilon^2\rho_2 + \cdots\cdots \\ p &= p_0 + \varepsilon p_1 + \varepsilon^2 p_2 + \cdots\cdots \\ v &= \varepsilon v_1 + \varepsilon^2 v_2 + \cdots\cdots \end{aligned} \tag{5}$$

where the ε represent a perturbation parameter, and the subscripts 0, 1, and 2 represent the static, first-order, and second-order quantities, respectively. Additionally, the relation between ρ and p is assumed to be linear [2],

$$p = c_0^2 \rho \tag{6}$$

Substituting Eqn. (5) and (6) into Eqn. (1) and (2), we can obtain the first-order acoustic equations,

$$\partial_t \rho_1 = -\rho_0 \nabla \cdot v_1 \tag{7}$$

$$\rho_0 \partial_t v_1 = -c_0^2 \nabla \rho_1 + (\zeta + 4/3\eta) \nabla\nabla\cdot v_1 - \eta \nabla \times \nabla \times v_1 \tag{8}$$

The same procedure is repeated for all the second-order terms, and the resulting equations are averaged over a full oscillation period *T*, can be described as $\langle X \rangle \equiv 1/T \int_0^T X dt$. According to this operation, the time-averaged, second-order perturbation can be shown in the follow form,

$$\langle \partial_t \rho_2 \rangle + \rho_0 \nabla \cdot \langle v_2 \rangle = -\nabla \cdot \langle \rho_1 v_1 \rangle \tag{9}$$

$$\rho_0 \langle \partial_t v_2 \rangle + \langle \rho_1 \partial_t v_1 \rangle + \rho_0 \langle (v_1 \cdot \nabla) v_1 \rangle = -\nabla \langle p_2 \rangle + (\zeta + 4/3\eta) \cdot \langle v_2 \rangle - \eta \nabla \times \nabla \times \langle_1 \tag{10}$$

Combining Eqn. (7)-(10) with appropriate boundary conditions, sound fields and acoustic streaming fields generated from vibrating bottom microcavity array can be solved numerically using COMSOL Multiphysics.