Reply to "Comment on 'Deformation of biological cells in the acoustic field of an oscillating bubble' "

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In the Comment by Choi *et al.* [Phys. Rev. E **82**, 013901 (2010)] on two our articles [Phys. Rev. E **72**, 061907 (2005); Phys. Rev. E **79**, 021910 (2009)], it is claimed that (a) there is more than one natural frequency associated with the quadruple mode and (b) the quadruple mode shows resonance more closely at the characteristic frequency $\omega_T/2\pi$ than at $\omega_K/2\pi$. In this Reply we would like to provide evidence supporting the conclusions made in our original articles.

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In the paper on natural oscillations of bacteria [1], we analyzed only one root of the dispersion equation of the natural vibrations (DENV) derived for bacteria. This choice was based on (a) consideration of bacteria vibration in a inviscid liquid and (b) analysis of the DENV of drops in the low-viscosity limit [2]. In the inviscid liquid, the DENV of bacteria, Eq. (39) in Ref. [1], has only one solution and, therefore, only a single resonance frequency, Eq. (42) in Ref. [1]. It is natural to assume that taking the viscosity of the liquid into consideration would lead to the damping of natural vibrations but not the appearance of a second high frequency resonance.

The DENV of drops and bacteria becomes a nonlinear one if the effects of liquid viscosity on vibrations of bacteria or a drop are included [1,3]. The common strategy to find a solution of the dispersion equation of a drop is to simplify the DENV, assuming that the effect of the liquid viscosity is small (low-viscosity limit). That approach was used by Prosperetti (see Ref. [2]) where a singular analytical root for the DENV of the drop was obtained. The solution of the dispersion equation of drops in the low-viscosity limit was obtained using the perturbation technique and we assumed that the viscosity itself only slightly changed the value of the resonant frequency. A simple analytical form of the dispersion equation of the drop in the low-viscosity limit was derived by Marston [4]. Again, only a singular solution was obtained for the frequency of the natural oscillations of drops.

It is surprising that the dispersion equation of *E. coli* has a second high frequency, 14.4 MHz root [5] (the natural frequency of the low frequency root was 2.9 MHz). However, the physical significance of this root is unclear. For instance, asymptotic analysis of the DENV for drops performed in the low-viscosity limits has shown that elastic effects give rise to the type of shape oscillations that do not depend on the surface tension [6]. The existence of this type of oscillation was related to the elasticity of the interior of the drop. The kind of forces responsible for natural vibrations at 14.4 MHz for *E. coli* was not identified in the comments. Can vibrations at 14.4 MHz for *E. coli* be excited by the external mechanical forces or by ultrasound? The answers to these questions were not given in the comments. As can be seen by the curves shown in Fig. 2 (Ref. [5]), the existence of this root does not change the behavior of the area deformation when the frequency of the sound is close to this root. Moreover, it is surprising that the 14.4 GHz frequency does not depend on the surface tension value T_o (see Fig. 1, Ref. [5]). Therefore, further studies should be done in order to understand with what kind of movement or deformation the second root of the dispersion might be associated with and whether it has any effect on the behavior of the cell in the ultrasonic field on the frequency response to any mechanical force.

Another comment stated that "the quadruple mode shows resonance more closely at the characteristic frequency $\omega_T/2\pi$ than at $\omega_K/2\pi$" in the above mentioned comments is related to the high value of the surface tension used in the simulation in Ref. [5]. Because the value of the surface tension of bacteria T_o is not known, we estimated its value by using a simple relationship $T_o=K_A\,\Delta S$, where ΔS is the initial relative change in the area of the cell. The maximal values of the area deformation $\Delta S_{\max}$ of a biological cell are known only for a few types of cells. For instance, $\Delta S_{\max}$ cannot exceed 5% in red blood cells. In our simulation [1,7] the value of $\Delta S_{\max}$ was chosen to be 10% and the value of the T_o assumed to be around 10% of K_A. The relationship $T_o=0.5K_A$ was used only for estimation of the modulus K_A, when the elastic moduli of bacteria were not measured. The author of the Ref. [5] attempted to estimate the value of the T_o, using the Laplace equation and obtained a very high value of the surface tension, T_o, of the bacteria cell, which is $0.84K_A$ for *E. coli* [5] according to their estimates. We believe that such a value of T_o is not realistic because it implies that the surface of a bacterial cell can be expanded by 84% without rupture of a cell wall. The high value of the T_o modulus leads to the high value of the characteristic frequency associated with T_o, $\omega_T/2\pi$ and therefore, to the not realistic deformation curve as function of frequency (Figs. 2 and 3 in Ref. [5]).

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