Cavitation and Heat Release Induced by Porous Silicon Nanoparticles with Various Surface Coatings for Biomedical Applications

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Background, Motivation and Objective

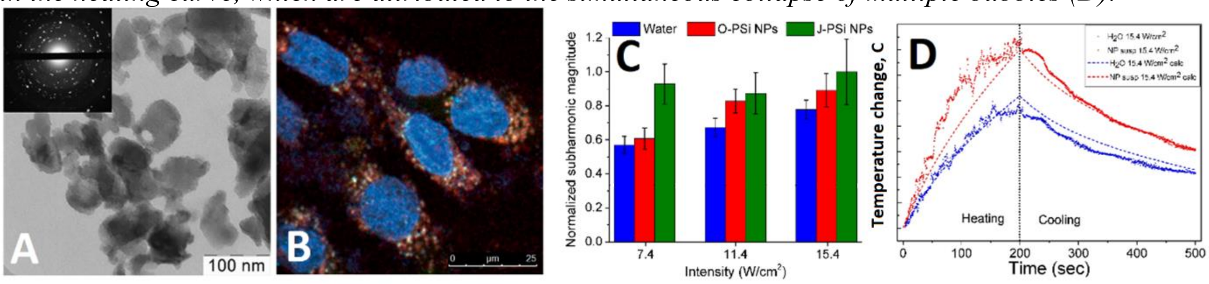
Luminescent nanoparticles based on porous silicon (PSi NPs, B) with a mean size of 100 nm (A) attract a lot of interest because of the outstanding properties of biocompatibility and biodegradability (B), as well as wide opportunities of the surface modification. Their developed surface and porous structure (A) are applicable for the targeted delivery of drugs and also opens new perspectives to improve the efficiency of current ultrasound-based treatment modalities like HIFU.

Statement of Contribution/Methods

The research was conducted through contributions of all authors. PSi NPs were synthesized by the process of electrochemical etching followed by ball milling. The outer surface of PSi NPs was chemically and thermally oxidized, while the inner surface was either oxidized or prevented from oxidation. Additional polymer coatings were used for biological experiments. The surface modification was controlled by IR spectroscopy, TEM and zeta potential measurements. The core experiment was carried out using a custom device consisting of a cuvette for samples, which was irradiated with a sinusoidal 2 MHz ultrasonic beam with variable intensity (1-15 W/cm^2) for several minutes. Cavitation intensity and thresholds were estimated by the subharmonic magnitude in the white noise spectrum. Temperature was controlled using miniature E-type thermocouples. Numerical simulation of heat deposition and cavitation dynamics were performed as well.

Results/Discussion

We revealed a double reduction of cavitation thresholds, as well as excess heating in the suspensions of PSi NPs as compared to distilled water (C, D). The effects were especially pronounced for the samples with hydrophobic non-oxidized pores, which stand as gas containers. The Laplace pressure is too high for nano-sized air bubbles to let them grow up to the sub-micron ones. But the appearance of subharmonic magnitude after some time lag must be an evidence of a synergistic effect of multiple air nuclei in the pores of PSi NPs on the bubble growth (C). The cavitation, in its turn, significantly influences the behavior of ultrasound-induced heating in the suspensions of PSi NPs. The local heating in the vicinity of collapsing bubbles can achieve extra high values, while the typical times of heat deposition are very small. Nevertheless, it is possible to detect significant temperature outbursts in the heating curve, which are attributed to the simultaneous collapse of multiple bubbles (D).



TEM image of porous silicon nanoparticles (A). The inset shows an electron diffraction pattern. Luminescent image of living CF2Th (dog thymus) cells with the incorporated nanoparticles (B). Blue and red colors correspond to the cell nuclei and nanoparticles, respectively. Subharmonic magnitude for pure water and suspensions of two types of silicon nanoparticles at different ultrasound intensities (C). Temperature change in the center of cuvette filled with pure water and a nanoparticle suspension at different ultrasound intensities (D). Curve oscillations reveal the influence of cavitation on the heating process.