Bio-acoustic signalling; exploring the potential of sound as a mediator of low-dose radiation and stress responses in the environment.

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Supplementary file 1: Relationship between absorbed dose and acoustic emission

We present a treatment of the relationship between absorbed dose and acoustic emission and identify parameters required to apply this general relationship to specific biomaterials and their environment. An electron-phonon interaction induced energy transfer with fast non-radiative relaxation of excited states of atoms/molecules that converts EM energy absorption into thermal expansion of heat which generates a pressure rise ΔP that can be described as follows (Gusev and Karabutov 1993)

$$\Delta P = \frac{1}{\gamma}\frac{\Delta V}{V} = \frac{1}{\gamma}\beta\Delta T$$

$$= \frac{1}{\gamma}\frac{\beta}{\rho C_v}E_{abs} = \frac{\beta\, v_s^2}{C_p}\,\mu_a \cdot F = \Gamma \cdot \mu_a \cdot F \qquad (1)$$

$$\Delta P = \Pi \cdot \mathrm{D} \qquad (2)$$

$$\Pi = \Gamma \cdot \rho_A \cdot \int_{\lambda_1}^{\lambda_2} \mu_a(\vec{r},t,\lambda)\cdot f(\vec{r},t,\lambda)d\lambda$$

$$= \frac{\beta \cdot v_s^2 \cdot \rho_A}{C_p} \cdot \int_{\lambda_1}^{\lambda_2} \mu_a(\vec{r},t,\lambda)\cdot f(\vec{r},t,\lambda)\, d\lambda \qquad (3)$$

The radiation flux or number of photon particles delivered per unit area and unit time represents the high energy photon fluence F[J/m^2].

The absorption coefficient distribution of photon for biological tissue represented by μ_a. The pressure acoustic wave propagates at the speed of sound v_s $[m/s]$ and it is specific to the properties of the biomaterial exposed to radiation. There is a direct relationship (Eq (2)) between the absorbed dose *D [Gy]* applied with the acoustic pressure generated. The absorbed dose *D [Gy]* (the energy deposited in matter by ionizing radiation per unit mass) represents the photon fluence F per area density (or mass thickness) $\rho_A = \rho.l$ with ρ the density and l the thickness or diameter of the biomaterial irradiated (Ahmad et al. 2015). A fractional variation of volume ΔV $[m^{-3}]$ of irradiated matter is caused by thermal expansion ΔT from an initial volume V exposed to radiation. This thermal expansion includes the thermal coefficient of volume expansion $\beta[K^{-1}]$ and $\gamma\,[Pa^{-1}] = \frac{1}{\rho\, v_s^2}\frac{C_p}{C_v}$ is the thermodynamic coefficient of isothermal compressibility. The thermal coefficient of volume expansion measures the fractional change in volume ΔV per degree change in temperature at a constant pressure. Each biological component irradiated has a heat capacity and it represents the amount of heat energy absorbed to raise the temperature of a unit of mass and temperature. The specific heat capacity in Eq (1) is represented at constant pressure with C_p and at constant volume with C_v.

The accumulated mechanical stress is proportional to the local optical fluence (F), photonic absorption coefficient (μ_a), and thermoelastic efficiency of the medium (Diebold and Wang 2009, Gusev and Karabutov 1993). The conversion efficiency between deposited heat energy and pressure is often represented as the Gruneisen coefficient Γ which is a material specific constant; a dimensionless temperature factor which is proportional to fraction of thermal energy converted to mechanical stress.

The proposed multicomponent parameter Π in this review incorporates the Gruneisen coefficient Γ, the area density (or mass thickness) and as well the photonic absorption coefficient (μ_a). The Gruneisen coefficient Γ is an approximation as it does not take into account the complexity of the bioenvironment surrounding the material irradiated and/or heterogeneous composition of the material at the biomolecular level linked to bystander effects. In order to understand and to be able to correctly predict the physics of the photoacoustic phenomenon in this case, accurate knowledge of the multicomponent parameter Π of the specific irradiated material as a function of temperature as well as function of the sum of the absorbance wavelength λ is required and determination of this for cells is an important priority.

This multicomponent parameter Π is an environment-specific material parameter which should include the complexity of the biological photonic signature of each component as well as their heat properties at specific emissive wavelength λ with a region of $[\lambda_1, \lambda_2]$ according to the minimum λ_1 and maximum λ_2 of the specific electromagnetic spectrum distribution of the photon power flux F(λ) included in Dose D(λ). It includes the shape of the distribution of the photon beam, the geometrical spreading of photon that correspond to the law of conversion energy and the scattering associated with the mass attenuation coefficient, and the density of different components of the biological environment expressed through the general theory of photon propagation. It includes $f(\vec{r}, t, \lambda)$ the fraction of environmental spatial loss factor (bio-photon, scattering) at a spatial coordinate $\vec{r}$ and time t. This includes the fraction of bio-photon particles as energy emitted by each biological component which will not be re-absorbed by the closest located biomaterial, and which will not lead to a temperature rise or pressure variation. Understanding the multicomponent parameter Π will help to understand the portion of physical energy and its heat, mechanical or photonic mechanism involved in the complex bystander initiators.

References

1. Ahmad M, Xiang L, Yousefi S, Xing L. 2015. Theoretical detection threshold of the proton-acoustic range verification technique. Medical Physics.42:5735-5744.
2. Diebold GJ, Wang LV. 2009. Photoacoustic monopole radiation: Waves from objects with symmetry in one, two and three dimensions London: Taylor & Francis Group.
3. Gusev VE, Karabutov AA. 1993. Laser optoacoustics.