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Simulation of Radon Short Lived Decay Daughters' Inhalation Using the Lung Compartment Model

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Abstract. Radon and its short-lived decay daughters are the main source of irradiation by natural ways for population. The Radon gas, exhaled from soil, water or construction material is producing by radioactive decay the following solid daughters: Po-218, Bi-214, Pb-214, and Po-214, which can attach to aerosols, and consequently penetrate the organism by inhalation. The human respiratory tract can be approximated by aid of a compartment model that takes into account the different anatomical structures exposed to contamination and irradiation, as well as the respective physiological processes. This model is associated to a mathematical equations system that describes the behavior of the radioactive material inside the body. The results represent the dose equivalent on different organs and tissues, as function of subject and the physical activity performed in contaminating environment.

Key words: compartment model, respiratory tract, inhalation, Radon Daughters, aerosol, equivalent dose, Reference Worker

Introduction

One anatomical model should be designed as a set of compartments and the connections between. In order to establish the compartments of concern, one should take into account the anatomy of the human body (particularly focused on the system that represents the intake ways of radioactive materials and their joint organs and tissues). The connections between compartments are performed when analyzing all the metabolic processes within, such as deposition and clearance (transportation and absorption), of concerned material.

Method

The anatomy of human respiratory system

In the case of Radon progeny, the first tract to be exposed is the respiratory one. The inhaled material (the Radon daughters attached to aerosols) is deposited in the main areas (i.e. the naso-pharynx (N-P), the trachea, the bronchi and the bronchioles (T-B), and the alveolar interstitium (P) - the gas exchange region), then cleared into the body by transportation and absorption mechanisms. Consequently, it should be taken into account the contribution of the radioactive material reaching the lymph nodes (LN), the gastro-intestinal tract (GI) and the body fluids (BF) – to be considered as joint compartments within the model (as in fig.1).

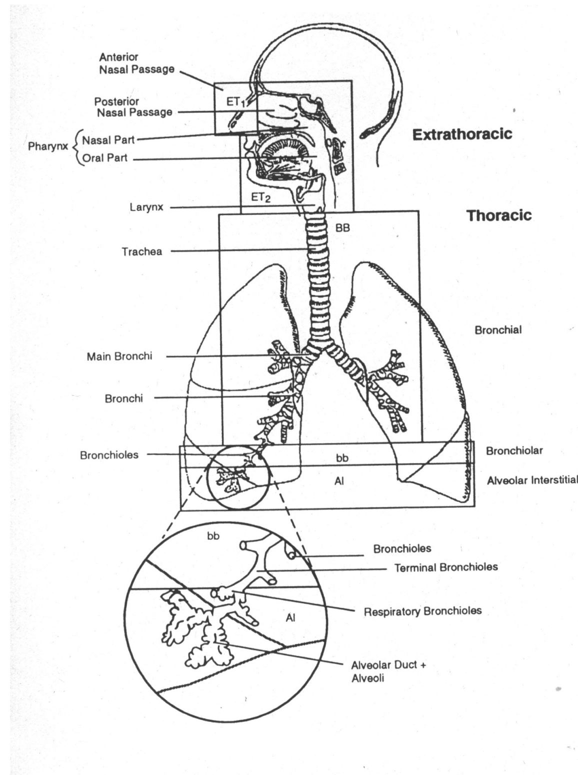

Fig. 1 - The human respiratory system

The compartment model

The main exposed organs and tissues are considered compartments of the current model (see Fig. 2). The inter-connections are performed according to the latest human physiology data [1], [2].

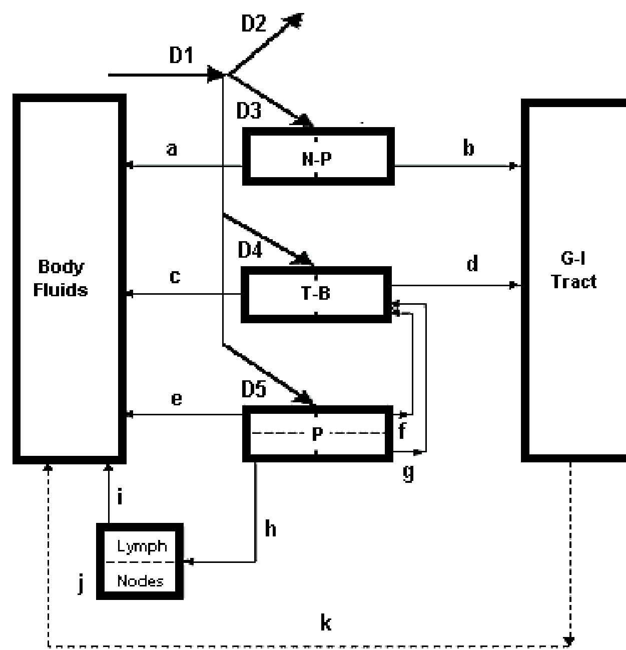

Fig. 2 - The compartment model

For each clearance way, it was considered one corresponding sub-compartment, as it follows:
a – for the rapid transfer into blood of material deposited in N-P;
b – for the muco-cilliary transport of material from N-P directly into the G-I;
c – for the rapid absorption of material from T-B in the vascular system, blood and the body fluids (BF);
d – corresponding to the muco-cilliary transportation from T-B into GI;
e – corresponding to material translocation from the alveolar region into blood (BF);
f – for the rapid clearance from pulmonary area (P) – via the T-B – making a deposit in G-I;
g - similar to f, but much slower, because of chemical structure and because of saturation phenomenon;
h – for slow elimination of material deposed into pulmonary area – via the lymph nodes – creating a deposit in the pool of body fluids; this process depends on the metabolism, phagocytosis and lymph drainage;
i – corresponding to the second way of clearance from the lymph nodes into blood; it depends on the particulates dissolving rate and the lymphocites renewal probability;
j – sub-compartment of the lymph nodes where the deposed material is kept for a very long, undetermined period;
k – corresponding to the way of material trasnsportation from the GI tract into the body fluids (BF); this particular way is not taken into account in this current study.

The equation system

According to the previous considerations, one should establish a set of differential equations:

$$\frac{d}{dt}q_a(t) = I(t)\cdot D_3 \cdot f_a - \lambda_a q_a(t) - \lambda_R q_a(t)$$

$$\frac{d}{dt}q_b(t) = I(t)\cdot D_3 \cdot f_b - \lambda_b q_b(t) - \lambda_R q_b(t)$$

$$\frac{d}{dt}q_c(t) = I(t)\cdot D_4 \cdot f_c - \lambda_c q_c(t) - \lambda_R q_c(t)$$

$$\frac{d}{dt}q_d(t) = I(t)\cdot D_4 \cdot f_d + \lambda_f q_f(t) + \lambda_g q_g(t) - \lambda_d q_d(t) - \lambda_R q_d(t)$$

$$\frac{d}{dt}q_e(t) = I(t)\cdot D_5 \cdot f_e - \lambda_e q_e(t) - \lambda_R q_e(t)$$

$$\frac{d}{dt}q_f(t) = I(t)\cdot D_5 \cdot f_f - \lambda_f q_f(t) - \lambda_R q_f(t)$$

$$\frac{d}{dt}q_g(t) = I(t)\cdot D_5 \cdot f_g - \lambda_g q_g(t) - \lambda_R q_g(t)$$

$$\frac{d}{dt}q_h(t) = I(t)\cdot D_5 \cdot f_h - \lambda_h q_h(t) - \lambda_R q_h(t)$$

$$\frac{d}{dt}q_i(t) = f_i \lambda_h q_h(t) - \lambda_i q_i(t) - \lambda_R q_i(t)$$

$$\frac{d}{dt}q_j(t) = f_j \lambda_h q_h(t) - \lambda_R q_j(t)$$

Where:
$q_a(t)$, $q_b(t)$, $q_c(t)$ etc. is the activity of inhaled radionuclide in compartments a, b, c, etc.;
I(t) – activity inhalation rate;
λ_a , λ_b , λ_c – biological clearance rates for compartments a, b, c, etc.;
λ_R – radioactive decay constant of radionuclide;
f_a , f_b , f_c – regional fractions cleared by the respective ways within the respiratory tract.

The analytical result of the equation system gives the resident amount of material to be found in an organ or tissue at t days after an unitary (1μCi) inhalation is:

$$X = \sum f_k \int_0^{\infty} e^{-(\lambda_k+\lambda_R)t} dt \quad (\mu Ci \cdot d), \quad \text{or} \quad X = \sum f_k \frac{\left(1-e^{-(\lambda_k+\lambda_R)t}\right)}{\lambda_k + \lambda_R} \quad (\mu Ci \cdot d)$$

If neglecting the integral: $X = \sum \frac{f_k}{\lambda_k + \lambda_R}$ $(\mu Ci.d)$

Where:

λ_R , f_k and λ_k are defined as above for k=a÷j;

$\lambda_k = \frac{\ln 2}{T_k} = \frac{0{,}693}{T_k}$; T_k is the half life by the k-way of clearance.

In accordance to the current model, each compartment will receive a specific amount of residual material:

$$X_{N-P} = D_3\left[\frac{f_a}{\lambda_a + \lambda_R} + \frac{f_b}{\lambda_b + \lambda_R}\right] \quad (\mu Ci \cdot d)$$

$$X_{T-B} = D_4\left[\frac{f_c}{\lambda_c + \lambda_R} + \frac{f_d}{\lambda_d + \lambda_R}\right] + D_5 \cdot \left[\frac{f_f \cdot \lambda_f}{\lambda_f + \lambda_R} + \frac{f_g \cdot \lambda_g}{\lambda_g + \lambda_R}\right] \cdot \frac{1}{\lambda_R + \rho} \quad (\mu Ci \cdot d)$$

$$X_P = D_5\left[\frac{f_e}{\lambda_e + \lambda_R} + \frac{f_f}{\lambda_f + \lambda_R} + \frac{f_g}{\lambda_g + \lambda_R} + \frac{f_h}{\lambda_h + \lambda_R}\right] \quad (\mu Ci \cdot d)$$

$$X_{G-I} = \frac{D_3 \cdot f_b \cdot \lambda_b}{\lambda_b + \lambda_R} + \frac{D_4 \cdot f_d \cdot \lambda_d}{\lambda_d + \lambda_R} + D_5\left[\frac{f_f \cdot \lambda_f}{\lambda_f + \lambda_R} + \frac{f_g \cdot \lambda_g}{\lambda_g + \lambda_R}\right] \cdot \frac{\rho}{\rho + \lambda_R} \quad (\mu Ci \cdot d)$$

$$X_{LN} = \frac{D_5 \cdot f_h \cdot \lambda_h}{(\lambda_h + \lambda_R)(\lambda_i + \lambda_R)} \quad (\mu Ci \cdot d)$$

$$X_B = \frac{D_3 \cdot f_a \cdot \lambda_a}{\lambda_a + \lambda_R} + \frac{D_4 \cdot f_c \cdot \lambda_c}{\lambda_c + \lambda_R} + \frac{D_5 \cdot f_e \cdot \lambda_e}{\lambda_e + \lambda_R} + \frac{D_5 \cdot f_h \cdot \lambda_h \cdot f_i \cdot \lambda_i}{(\lambda_h + \lambda_R)(\lambda_i + \lambda_R)} \quad (\mu Ci \cdot d)$$

where $\rho = 33.3$ (d^{-1}) corresponds to the mean time of transit in T-B.

The equivalent dose calculation. The equivalent dose is calculated for each organ at risk / compartment, according to its weight and burden.

$$DE_k = \frac{51}{M_k} \sum_j \sum_i \left[X_j \cdot p_i \cdot E_i \cdot (QF)_{ik} \cdot (AF)_{ijk}\right] \cdot I \cdot 0.001 \cdot 0.0027$$

where:

DE_k – the equivalent dose on organ/tissue “k” (mSv)

M_k – the organ / tissue weight (g);

X_j – resident quantity in organ / tissue "j" (μCi.d);
E_i – radiation energy (α or β) of particle "i" (MeV);
51 – transformation factor (g.rad/MeV) x desintegration / μCi.d;
$(QF)_{i\,k}$ – quality factor of "i" radiation emitted in organ "k";
$(AF)_{i\,j\,k}$ – absorbed fraction of energy in organ "k" for when a particle of "i" type is getting disintegrated in organ "j";

For α and β radiation: $(AF)_{i\,j\,k} = \begin{cases} 0, & \text{for } j \neq k \\ 1, & \text{for } j = k \end{cases}$ and $(QF)_{i\,k} = \begin{cases} 20, & \text{for } \alpha \text{ radiation} \\ 1, & \text{for } \beta \text{ radiation} \end{cases}$

p_i – probability of disintegration for the "i" particle;
I – intake (kBq) = (radioactive concentration in air) x (respiration rate) x (time of exposure)
The other coefficients come from the transformations (g → kg) and (kBq → μCi).

Hypotheses

The computer software ModeLung [3] is used for assessing the internal doses coming from the inhaled Radon Daughters (α and β emitters): Po-218 (α), Pb-214 (β), Bi-214 (β), Po-214 (α).
The source organ and the target organ are considered as one and only, due to the short range of α and β radiation.

The software is not taking into consideration the second order progeny, as result of disintegration inside the body. The presented results are obtained for radioactive equilibrium condition among Rn and RnD.

All Radon Daughters (RnD) are considered as attached to aerosols.All RnD are D (day) class nuclides – absorbed within the organs in less than 10 days. All data are computed for a 6 hours continuous inhalation in an environment with a unitary concentration of activity (1kBq/m^3 – Radon equivalent concentration). The ModeLung software is able to offer results for a non-equilibrium condition, as defined by the user.

For radiation protection purposes, one should calculate the irradiation level for workers performing activity in contaminating environment. The radioactivity concentration in air, aerosol size, duration and type of labor in environment, as well as subject's physical and physiological data should be taken into account. Since the Radon Daughters are alpha emitters, their main target is the respiratory tract with its organs and tissues. The subject chosen for this study is the Reference Worker, with all its anatomical data as considered in International Commission on Radiological Protection, Publication no.66 [1]. 4 cases of a Reference Worker have been discussed, as it follows: normal nose breather performing usual labor (respiration rate 1.2 m^3/h); habitual mouth breather performing usual labor (respiration rate 1.2 m^3/h); normal nasal augmenter performing heavy work (respiration rate 1.7 m^3/h); habitual mouth breather performing heavy work (breathing rate 1.7 m^3/h).

Results

Equivalent doses to the naso-pharynx

As presented in Fig. 3, the normal nose breather receives the maximum equivalent dose for 7μm aerosols.

The habitual mouth breather receives a maximum equivalent dose for aerosols from 15 up to 20μm.

The minimum equivalent dose, for all case, is received for 0.1μm aerosols.

The equivalent doses received by the N-P region of nose breathers are higher than the ones received by the N-P of mouth breathers.

The equivalent doses for the subjects performing an intense activity are higher than for the subjects performing an usual activity.

Equivalent doses to the trachea and the bronchial tree

The equivalent dose for the T-B is much less than the dose on the N-P of the same subject (see Fig. 4).

The maximum equivalent dose on T-B is received for 0.003µm aerosols, and a second peak is found at 3÷5µm.

The second peak is probably corresponding to the venue of material from the P region, which is crossing the T-B in its way to the Gastro-intestinal tract.

The minimum equivalent dose is received for 0.3÷0.5µm.

For aerosols of larger size (up from 0.3µm), the habitual mouth breather will receive a higher dose on the T-B than the normal nose breather, no matter the activity.

Equivalent doses to pulmonary region

The equivalent doses in the alveolar/pulmonary region are much lower than the ones from the tracheo-bronchial region (Fig. 5).

For small aerosols, there is low difference between doses received by nose breathers and the mouth breathers.

For large aerosols, the difference is significant: the mouth breathers receive high radiation doses.

The maximum equivalent doses are received by the pulmonary region for 0.01÷0.02µm aerosols. A second peak may be observed at 2÷3µm. Because of abundant deposition of such aerosols, that particular peak can be related to the second peak of equivalent doses on T-B (compartment which is transited in two waves by the material from P to G-I).

Equivalent doses to the lymph nodes

The graph for the equivalent dose received by the lymph nodes is very similar to the one of the alveolar/pulmonary region, since the respiratory tract lymph nodes are provided with material from only P region (see Fig. 6).

The doses are 10 times lower than in the P region.

Equivalent doses to the blood and body fluids

The graph of equivalent doses received by the body fluids (Fig. 7) is a combination of graphs for N-P and T-B, the main material providers to the blood.

The minimum equivalent doses are received as consequence of 0.1µm aerosols inhalation.

The maximum doses are received for 0.002µm aerosols.

A second peak was obtained for 7µm aerosols.

Equivalent doses to the gastro-intestinal tract

The graph of equivalent doses to the gastro-intestinal tract (Fig. 8) is a combination of the obtained graphs for N-P and T-B, which are the only material providers to the G-I.

For smaller aerosols, the equivalent doses will be higher for mouth breathers.

For medium sized aerosols, the nose breathers will be more exposed to the gastro-intestinal tract.

For large aerosols, the respiration type doesn't count, but the respiration rate or activity.

Conclusions

First observation it can be made is that the Naso-Pharynx and the Tracheo-Bronchial regions receive higher equivalent doses than any other internal organ or tissue. Both curves show a minimum value for 0.1µm aerosols, no matter the subject and work conditions. Consequently, the organ weighted equivalent doses and finally the effective dose will be the lowest for 0.1µm aerosols.

It can generally be stated as well, that the smaller aerosol, the higher equivalent dose on Naso-Pharynx and Gastro-Intestinal tract. Fortunately, for such aerosols, there is low attachment probability to RnD.

For Tracheo-Bronchial and Body Fluids, there is a maximum of equivalent dose for 0,002µm aerosols.

The gas exchange region (the Pulmonary region), and the Lymph Nodes are more exposed to Radon daughters attached to 0.01µm aerosols, and less exposed towards both extremes of aerosols size range.

The normal nose breather is subject to higher doses to the naso-pharingeal region and the gastro-intestinal tract.

The habitual mouth breather receives higher doses to the tracheo-bronchial system.

References

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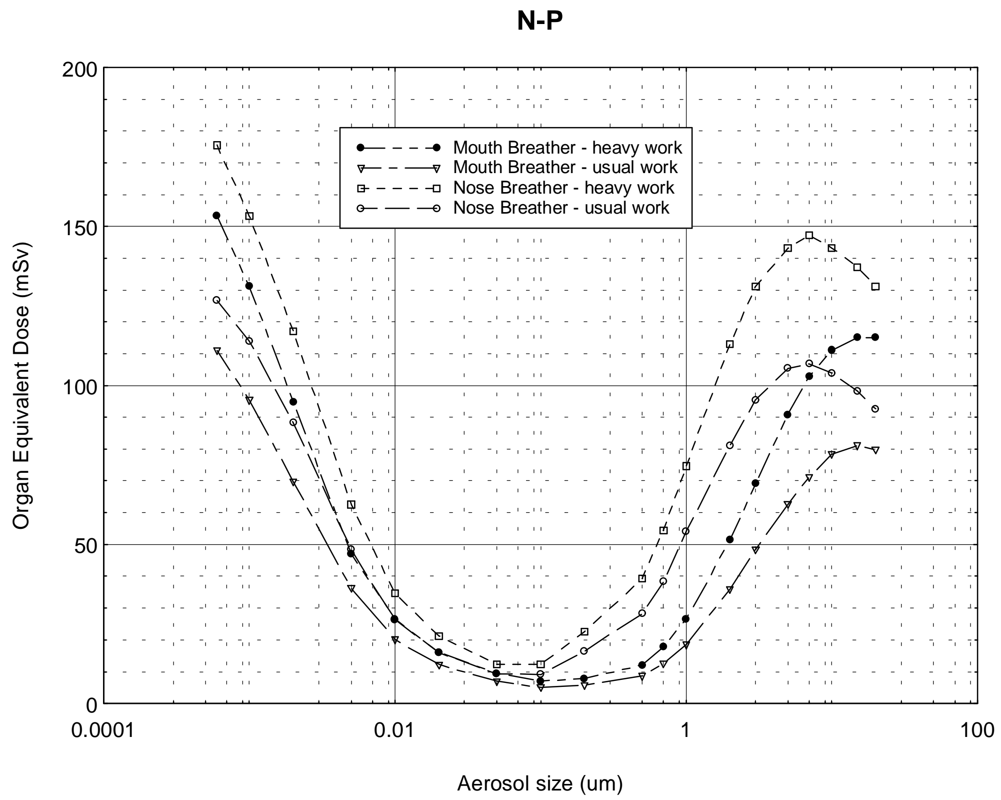

Fig.[3]. Equivalent doses for the naso-pharynx region

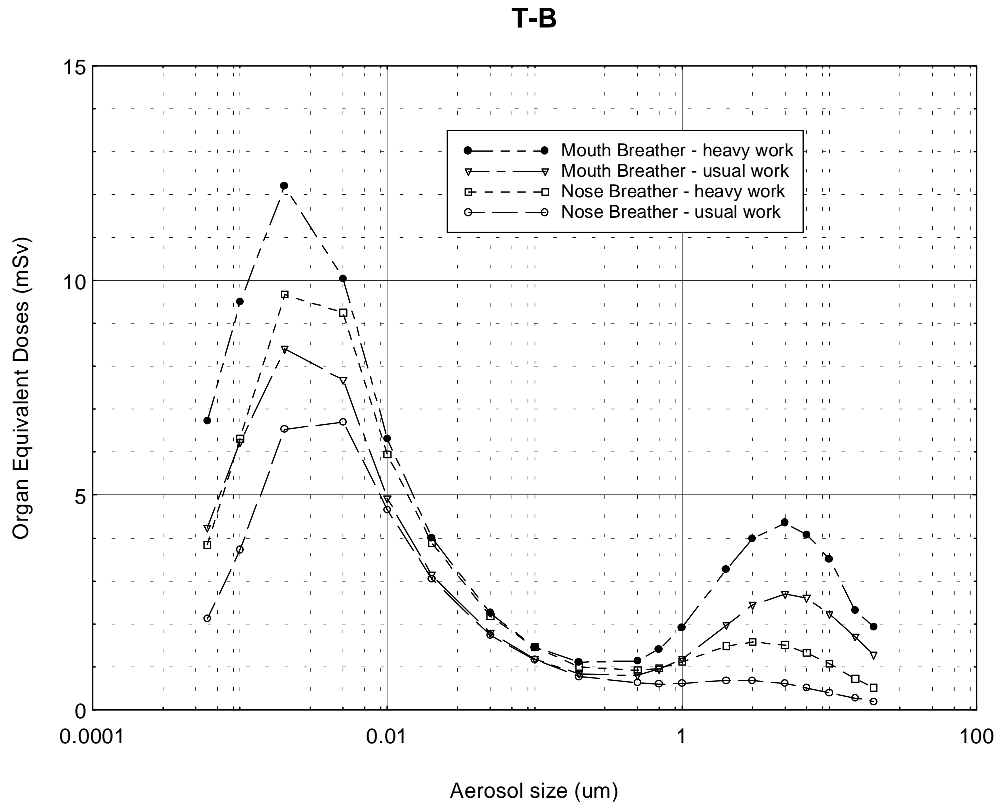

Fig. [4]. Equivalent doses to the tracheo-bronchial region

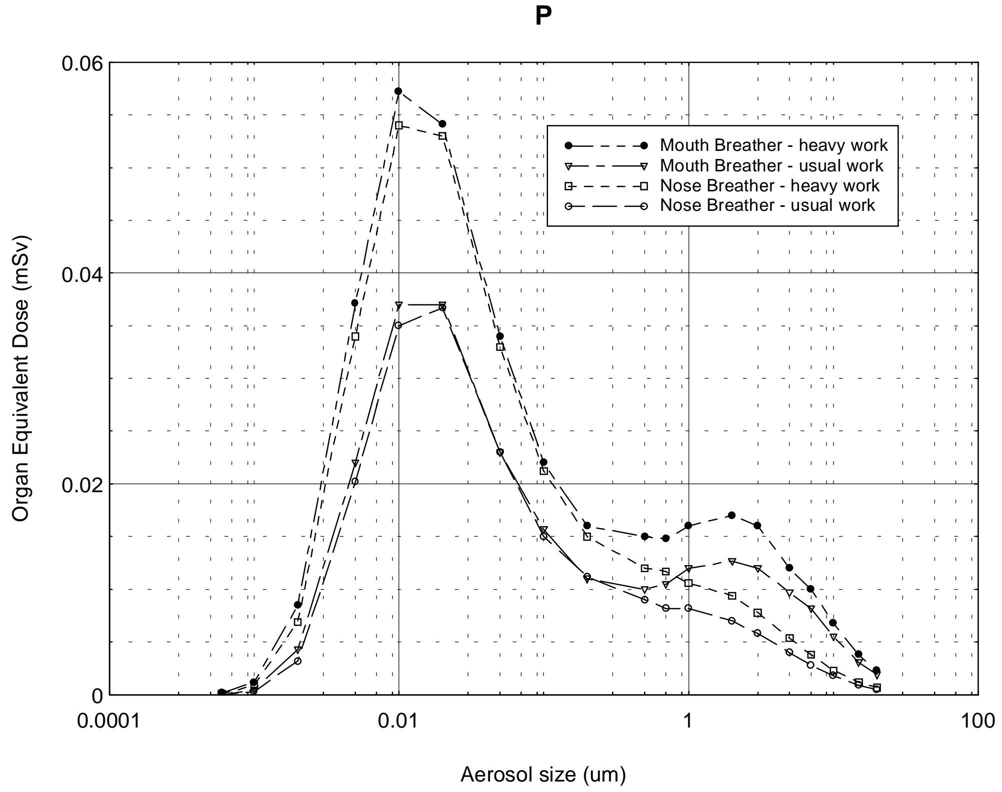

Fig. [5]. Equivalent doses to the pulmonary region

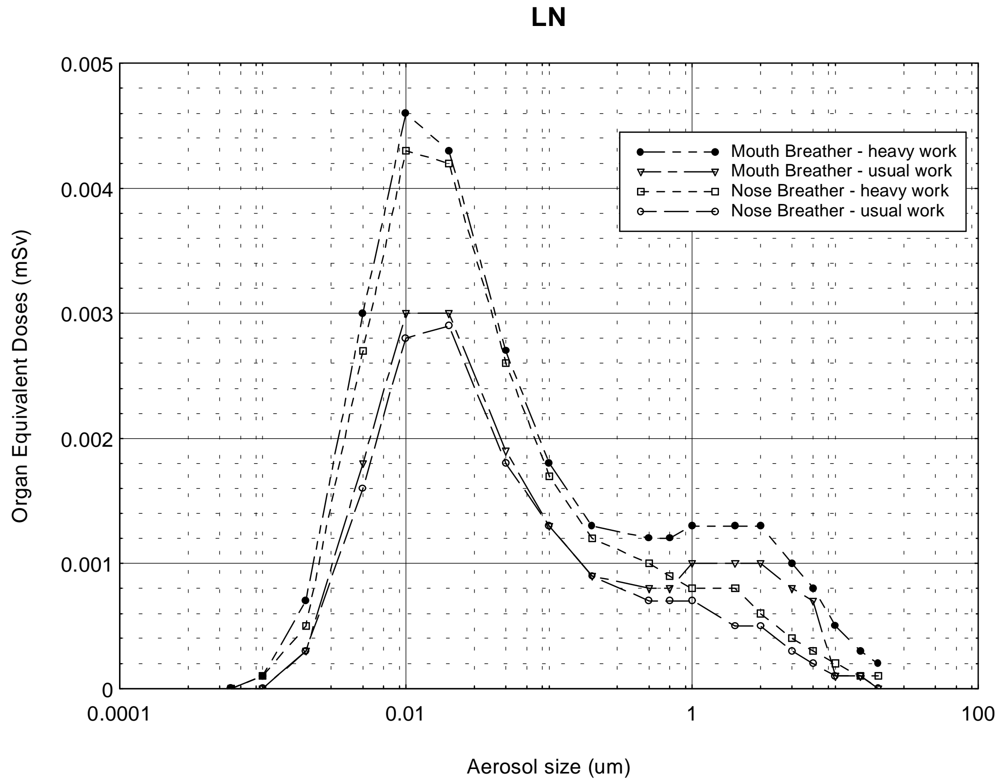

Fig. [6]. Equivalent doses to the lymph nodes

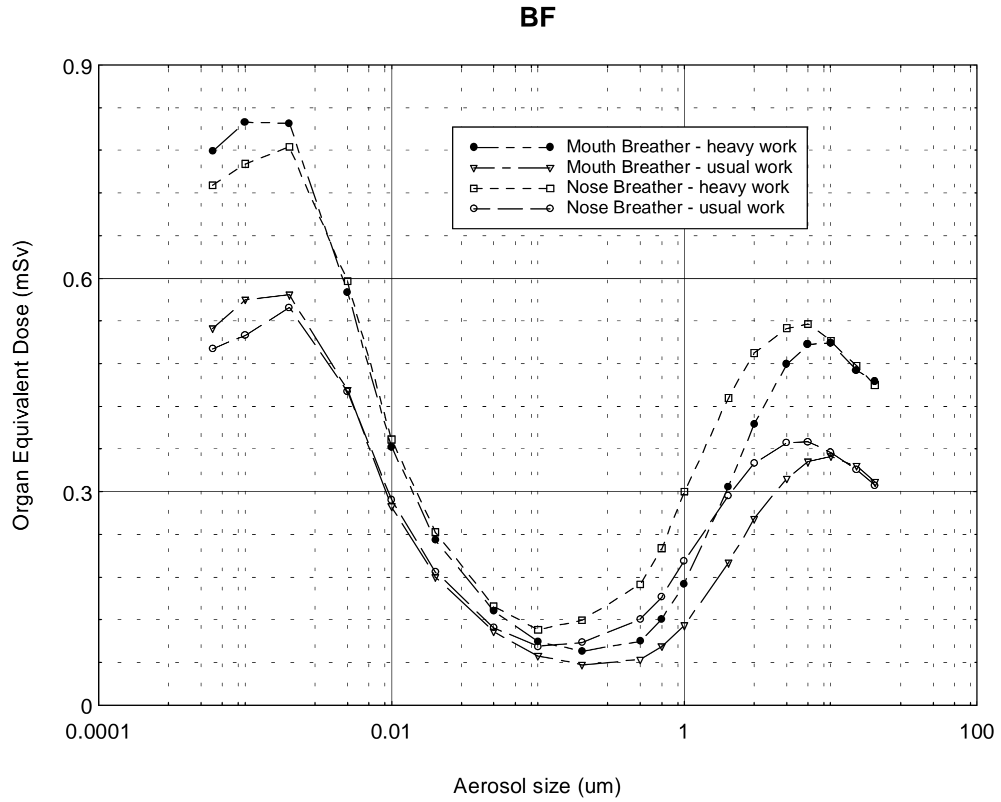

Fig. [7]. Equivalent doses to the body fluids

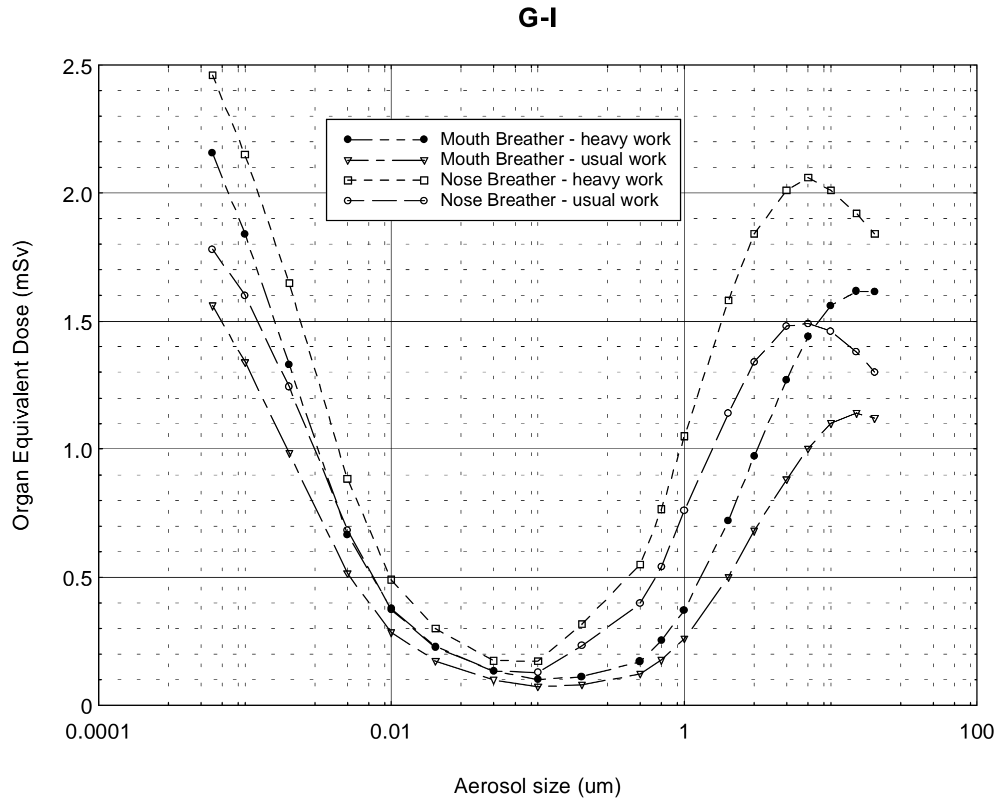

Fig. [8]. Equivalent doses to the gastro-intestinal tract