Modeling of the chemical stage in water radiolysis using Petri nets

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Abstract. The biological effect of ionizing radiation is mediated practically always by the clusters of radicals formed by densely ionizing track ends of primary or secondary particles. In the case of low-LET radiation the direct effect may be practically neglected and the radical clusters meet a DNA molecule always some time after their formation. The corresponding damage effect (formation of DSB) depends then on the evolution running in individual clusters, being influenced by present chemical agents. Two main parallel processes influence then final effect: diffusion of corresponding radical clusters (lowering radical concentrations) and chemical reactions of all chemical substances present in the clusters. The processes running in the corresponding radical clusters will be modeled with the help of continuous Petri net, which enables us to study the concurrent influence of both the processes: lowering concentration of radicals due diffusion and due chemical reactions. The given model may be helpful especially when the effect of radicals on DSB formation (DNA damage) at the presence of different substances influencing radiobiological effect is to be studied.

1. Introduction
The biological effect of ionizing particles consists in principle always of three stages; physical, chemical and biological. The damage of DNA molecules in individual cells under standard conditions is caused by different radicals formed in corresponding water medium, as direct effect caused by primary or secondary charged particles may be practically neglected. The biologically efficient damage of DNA molecules (formation of DSB mainly at lower-LET radiation) may be then given by radicals formed in clusters by densely ionizing track ends of individual particles. Before meeting a DNA molecule these radicals react mutually or with some other species being present in corresponding water medium; the number of efficient radicals may be lowered or heightened by these additional reactions.

Two main parallel processes will be assumed to be running within a cluster: chemical reactions of radicals having been formed at energy transfer and contemporary cluster diffusion. Both the parallel processes will be then simulated with the help of Continuous Petri nets.
2. Mathematical model of chemical and diffusing processes

We shall assume for simplicity that diffusion goes in a limited spherical volume (see Pimblott and Mozumder, 2004). The average concentration $c_i(r,t)$ representing the time dependence of concentration distribution of species $i$ may be given by

$$c_i(r,t) = \frac{N_i}{8\sqrt{\pi D_i t^3}} e^{\frac{-r^2}{4D_i t}},$$

where $D_i$ are corresponding diffusion coefficients and $t$ is the time from the start of diffusion in the theoretical center of given cluster, $r$ denoting the distance from cluster center. The time dependence of the cluster volume may be then defined as

$$V_i(t) = \frac{256}{3} \left[ \sqrt{\frac{D_i^3 t^3}{\pi}} \right].$$

We will now simulate the dynamics of chemical processes with the help of continuous Petri nets. The time change of the continuous places $P_i$ is via continuous transitions $T_{i+j}$. The time change of number $N_i$ of species $i$ may be then expressed with the help of the set of continuous transitions $T_{j+k}$:

$$\frac{dN_i(t)}{dt} \equiv T_{(i+j)}^{(i)} = -k_{ij} \frac{N_i(t) N_j(t)}{V_j(t)},$$

or

$$\frac{dN_i(t)}{dt} \equiv T_{(j+k)}^{(i)} = V_i(t) k_{jk} \frac{N_j(t) N_k(t)}{V_j(t) V_k(t)}.$$

The transition (3) expresses the speed of number decrease of species $i$ ($N_i$) due to reaction of species $i$ with species $j$ and the transition (4) expresses the speed of number increase of species $i$ ($N_i$) due to reaction of species $j$ with species $k$ for $j, k \neq i$.

It is, of course, necessary to use the value of volume $V_i(t)$, which corresponds to individual species $i$ as the result of diffusion into the surrounding. The increase of this volume occurs via continuous transitions $T_i$

$$\frac{dV_i(t)}{dt} \equiv T_i = 128 \left[ \sqrt{\frac{D_i^3 t}{\pi}} \right].$$

We can express the continuous places and continuous transitions graphically (see Fig. 1), places being represented by circles and transitions by rectangles.

3. Specification of the model according to data kind

We shall assume that the radicals considered in Table 1 may be responsible for radiobiological effect (see Chatterjee at al., 1983). Only the following radicals will be assumed to exist in radical clusters formed during energy transfer: $H^*$, $OH^*$, $e_{aq}$ and $H_3O^+$.

To demonstrate the application of Petri nets we shall use the results of our earlier analysis (Barilla at al., 2013, see also Barilla at al., 2000) of data presented by Blok and Loman (1973) and showing the dependence of DSB number (in a DNA molecule) on oxygen concentration at irradiation by photons emitted by Co-60 isotopes; without repeating the given procedure with the help of given nets.
If the chemical reactions shown in Table 1 have been considered it has been derived that the average size of efficient radical clusters is approximately 20 nm and average initial numbers of corresponding radicals (at oxygen saturation) 

$$N_H = 1.3, \quad N_{OH} = 17.2, \quad N_e = 14.8, \quad N_{H_3O} = 18.8.$$ 

The time dependencies of individual species concentrations that may be derived when Petri nets have been applied to are shown in Fig. 2.

4. Conclusion
It may be seen that OH radicals and aqueous electrons possess the highest concentrations that decrease quickly especially for aqueous electrons. Main radiobiological effect is caused surely by OH radicals as it is assumed commonly. The initial increase of H radicals may be regarded as interesting being probably in relation to reaction 7 in Table 1.
Concentrations of individual chemical species depending on time

The given results correspond to the case when the water has been saturated by oxygen. The use of Continuous Petri nets has simplified significantly the earlier approach of considering the roles of diffusion process and chemical reactions of individual radicals concurrently. They have made it possible to follow easily also the time dependencies of the concentrations of radicals and other species during cluster diffusion. The model may be easily extended to involve the influence of other species or radiomodifiers being present (at different concentrations) in water medium during irradiation. It may be very helpful in studying the influence of different stages of radiobiological process on final radiobiological effect in living cells.

References

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