Do Pure Water-Radiolysis Experiments Truly Unlock the Secrets of the FLASH Effect? A Numerical Revelation

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Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

NAmur Research Institute for LIfe Sciences

FRPT FLASH RADIOTHERAPY & PARTICLE THERAPY 2023 TORONTO & ONLINE 5 – 7 DECEMBER 2023

Do Pure Water-Radiolysis Experiments Truly Unlock the Secrets of the FLASH Effect? A Numerical Revelation

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Background and Aims

Reduced production of Reactive Oxygen Species (ROS) offers a potential explanation for the FLASH effect observed at ultra-high dose rates (UHDR). Recent studies consistently demonstrate decreased hydrogen peroxide (H_2O_2) generation in pure water under UHDR conditions. Additionally, the nature of irradiating particles significantly influences this phenomenon. This research aims to investigate ROS formation and decay kinetics in both FLASH and conventional conditions, spanning various Linear Energy Transfer levels and particle types.

Python 3.11

Simulated Volume

"K Reaction" Kinetics

→ Simple reactions like
A + 2B -> B + D
With R = [A] x [B]² x k
k -> Rate constant [mol.L⁻¹.s⁻¹]
R -> Reaction Rate [M.l⁻¹s⁻¹]

Redox Equilibrium

$\rightarrow HA^{\cdot} \underset{k_{a2}}{\overset{k_{a1}}{\rightleftarrows}} H^+ + A^{\cdot -}$

Radiolytic Reactions

→Production of species due to irradiation
(-> LET dependent)
$[e_{aq}^-, OH^{\cdot}, H^{\cdot}, H_2, H_2O_2, H_3O^+, R^{\cdot}]$

Enzymatic Reactions

$E + S \overset{k_1/k_{-1}}{\longleftrightarrow} [ES] \overset{k_2}{\rightarrow} E + P$
E -> Enzyme
S -> Substrate
P -> Product
ES -> Enzyme-Substrate complex

➔ *Homogeneous system chemically isolated from environment*

Method: Radio Kinetic model

Input file parser

Species initialization

Beam Definition

Building reactions matrices

Resolve ODE system (scipy-LSODA solver)

Time evolution of concentrations and reaction rates

Based on the work of R. Labarbe (2020) 10.1016/j.radonc.2020.06.001

Water radiolysis model:
- 31 reactions
- + 3 Acid-base reactions

➔ Total: 34 reactions + Radiolytic reactions

Biological model:
- SOD
- Catalase
- Lipid peroxidation scheme

➔ Total: 13 reactions

- Homogeneous irradiation
- No direct Damage
+ Temporal evolution over minutes
+ Complex chemical network
+ Low computation resources
+ Easy to evolve

Comparison with Pure Water Radiolysis experiments: 4% O_2 (Biology not activated)

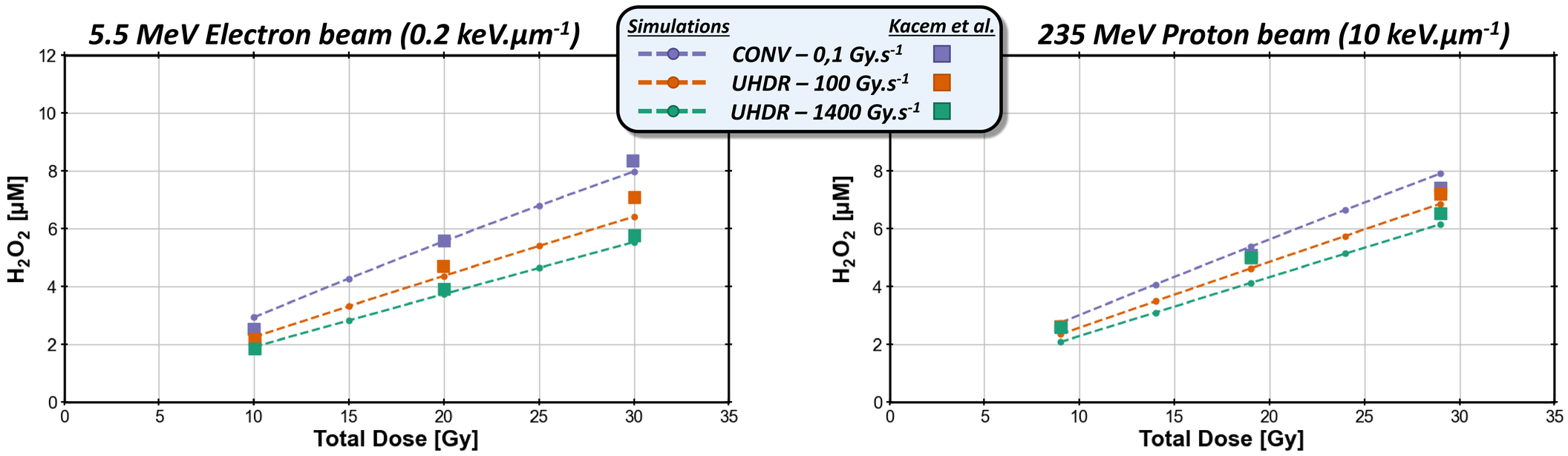

Fig.1: Concentrations of H_2O_2 after irradiation, measured (squares from H. Kacem, 2022, doi:10.1016/j.radonc.2022.07.011) and simulated (dotted lines)

Biology Activated (Focus on the 20 Gy case)

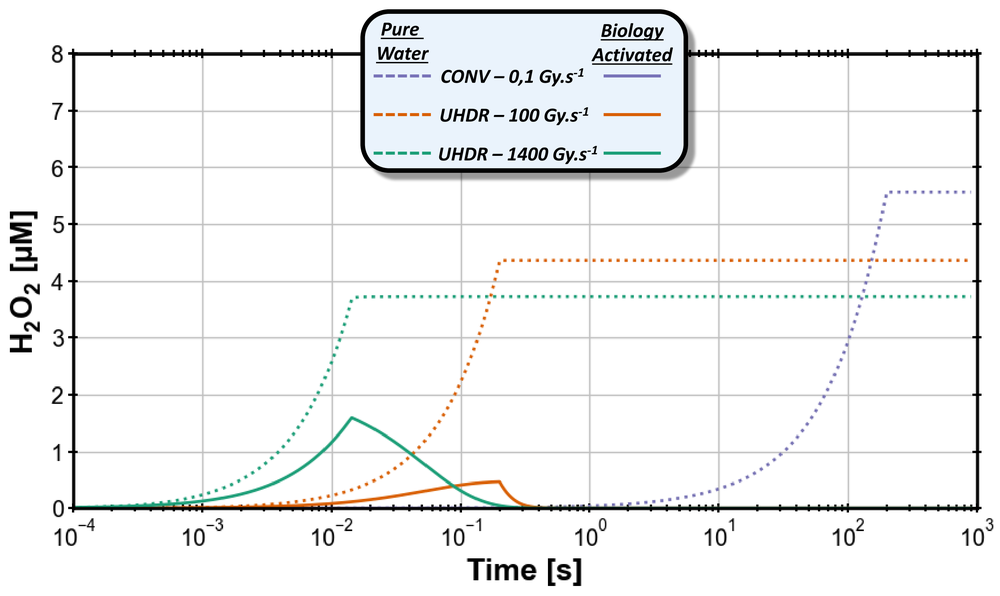

Fig.2: Time Evolution of the concentration of H_2O_2

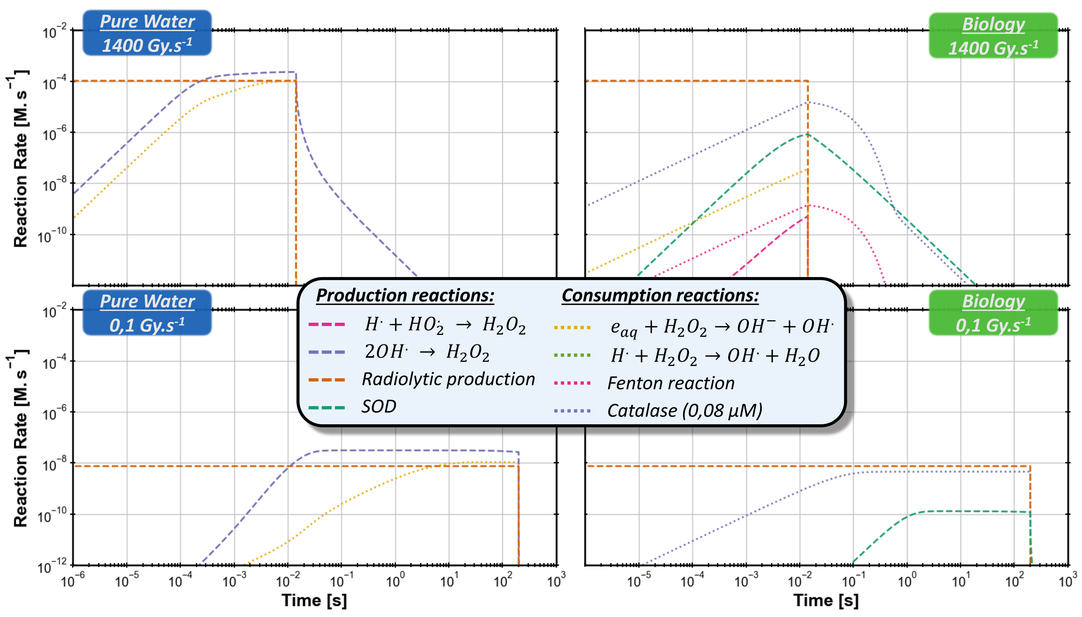

Fig.3: Time Evolution of the reaction rates of reactions involving H_2O_2

Conclusion

A distinct correlation emerges between UHDR and decreased H_2O_2 levels in pure water, aligning with established experimental data. Nevertheless, the association wanes notably when enabling cellular systems, primarily due to the potent ROS scavenging abilities inherent to cells. The translational applicability of water radiolysis findings to biological contexts remains an open inquiry, carrying profound implications for our comprehension of the FLASH effect in radiotherapy.

Acknowledgments

EPT (Emerging protontherapies) project (Mecatech and BioWin poles), Convention n° 8341, 2020-2024. Partners: IBA, Dekimo, V2i, UNamur, KUL, UCLouvain, UNantes

ARN Nuclear reactions analysis

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