The dose enhancement obtained by placing gold atoms and gold nanoparticles in the target volume in high-energy X-ray treatment

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Gold nanoparticles have shown potential to be used as a radiosensitizer in radiotherapy.

Y. Lin et al., Phys. Med. Biol. 59, 7675 (2014).
I. Martinez-Rovira and Y. Prezado, Med. Phys. 42. 6703 (2015).
Z. Kuncic and S. Lacombe, Phys. Med. Biol. 63, 02TR01 (2018).
W.Z. Xie et al., Phys. Med. Biol. 60, 6195 (2015). [5] K. Eun Ho et al., Oncotarget 8, 112390 (2017).
M. Douglass et al., Med Phys. 40, 071710 (2013).
R. Ahmad et al., Phys. Med. Biol. 61, 4537 (2016).
Y. Lin et al. Med. Phys. 42, 5890 (2015).
W. N. Rahman et al., Nanomedicine 5, 136 (2009).

The main aim of this work:

A numerical microdosimetry study of the influence of the gold nanoparticle size on the dose enhancement by placing gold atoms and large gold nanoparticles in the target volume in teleradiotherapy.

The considered therapeutic beams:
6 MV X-rays and 20 MV X-rays.

The used method:
Monte Carlo simulations based on GEANT4

Details

The main mechanism of the dose enhancement:
increase of the photoelectric effect yield.

The cross section σ of interaction by photoelectric effect:

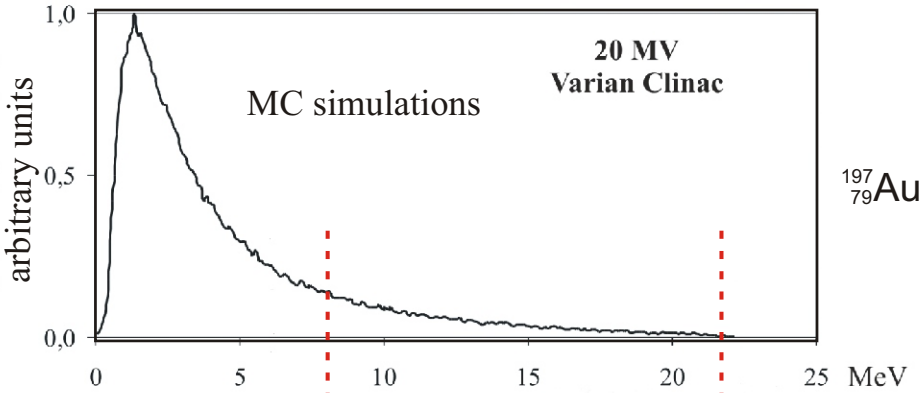
$$\sigma = \text{constant} \cdot \frac{Z^n}{E^3}$$

Z - atomic number,
n - a number which varies between 4 and 5,
E - energy of photons.

Location of gold atoms or gold nanoparticles in tumor increases a mean number of electrons per a unit volume in the irradiated volume.

The additional contribution to the dose enhancement:
radiation from decays of gold radioisotopes originating from reactions (γ,n) and (n,γ).

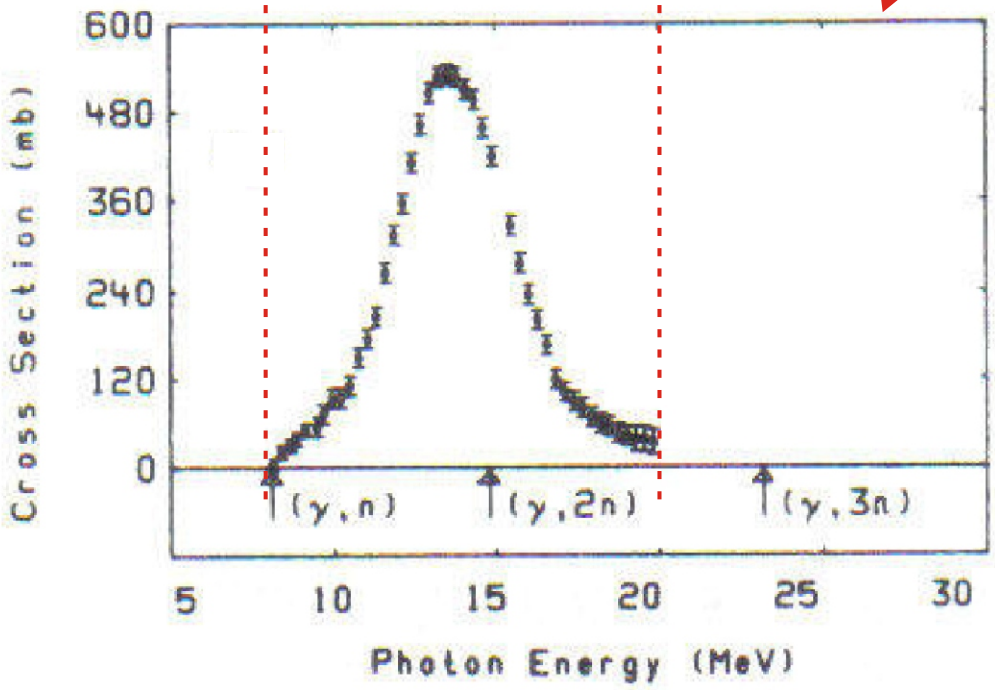
1) Photonulear reactions (γ,n)



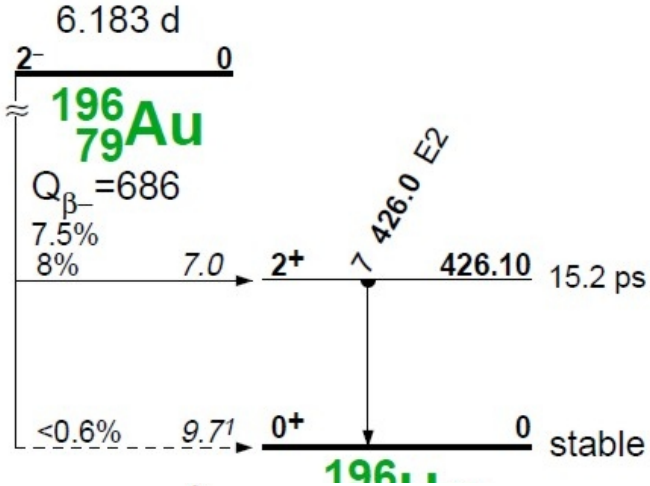
$^{197}_{79}Au$ (100%) + γ ⟶ n + $^{196}_{79}Au$

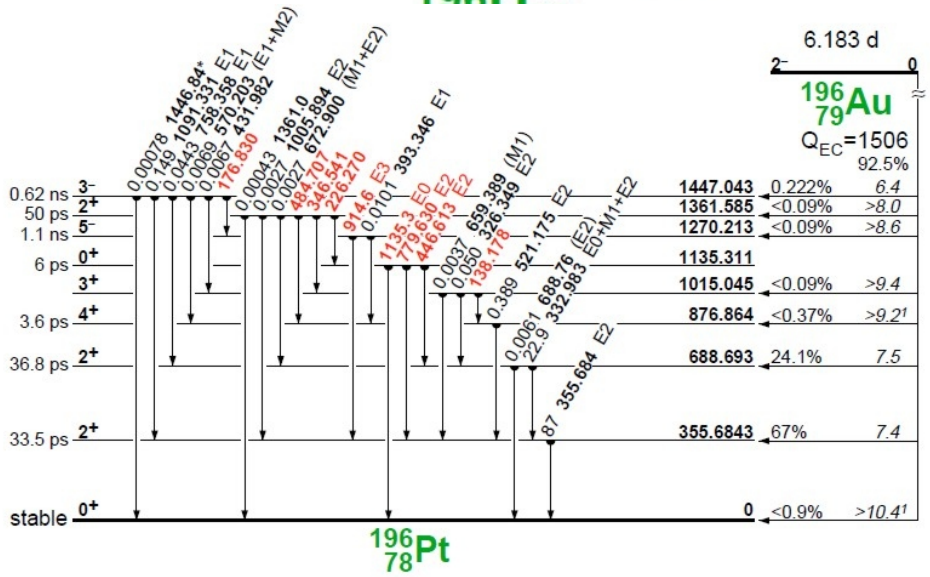
93% EC+β⁺ $T_{1/2}$ = 6.183d → $^{196}_{78}Pt$* → γ (332.98 keV (23%); 355.68 keV (87%)) → $^{196}_{78}Pt$ (stable), $T_{1/2}$ < 40ps

7% β⁻ $T_{1/2}$ = 6.183d → $^{196}_{80}Hg$* ($T_{1/2}$ = 6.183d) → γ (426.09 keV (100%)) → $^{196}_{80}Hg$ (stable), $T_{1/2}$ < 15ps ($T_{1/2}$ ≤ 15p)



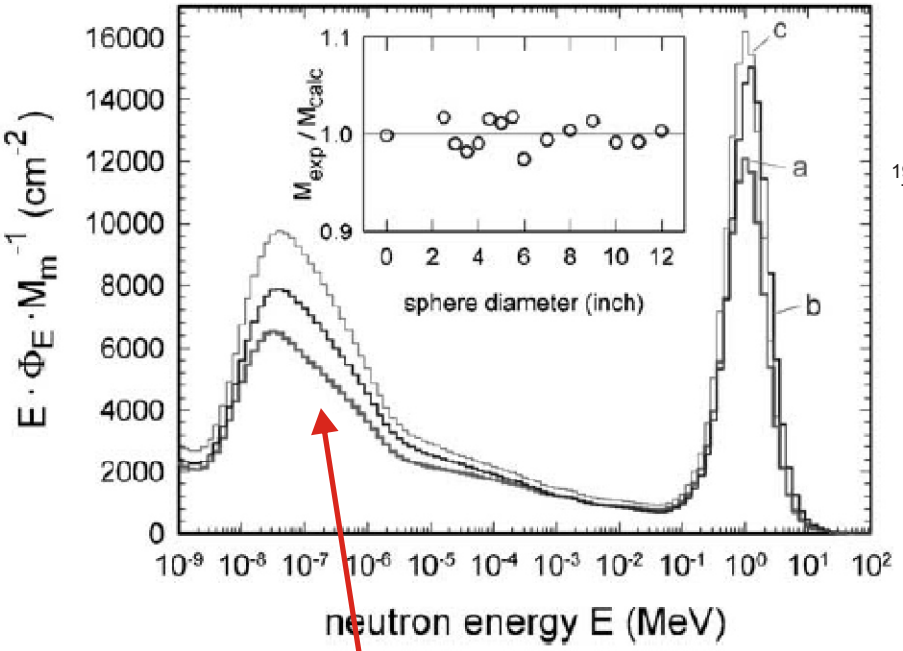
Dietrich, S.S., Bermab, B.L., 1988. Atlas of photoneutron cross sections obtained with monoenergetic photons. Atomic Data Nucl. Data Tables 38, 199-338.



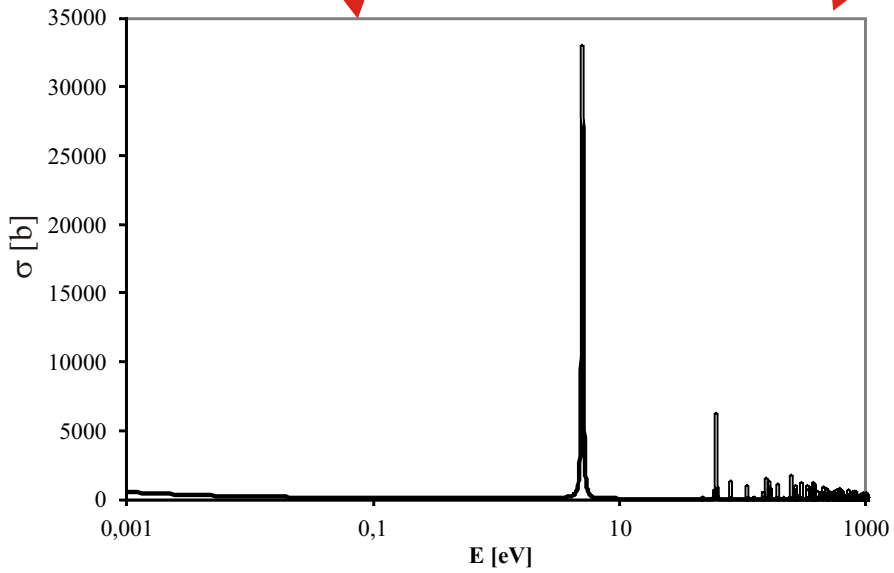


Neutron spectra on treatment couch

2) Simple capture reaction (n,γ)



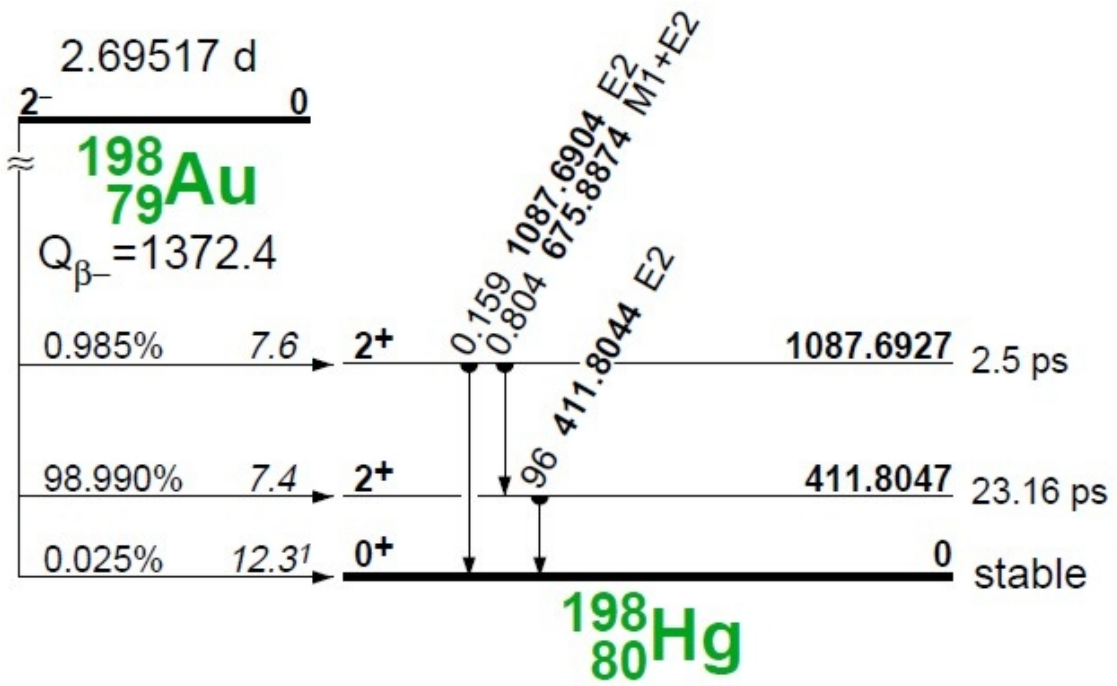
H. Schraube et al. Nuclear Instruments and Methods in Physics Research A 476 (2002) 463–467



Evaluated Nuclear Data File (ENDF), released December 22, 2011, http://www.nndc.bnl.gov/exfor/endf00.jsp

$^{197}_{79}Au$ (100%) + n → γ + $^{198}_{79}Au$ $\xrightarrow[T_{1/2}= 2.7d]{\beta^-}$ $^{198}_{80}Hg^*$ $\xrightarrow[T_{1/2}\approx 23ps]{\gamma}$ $^{198}_{80}Hg$ **(stable)**

411.80 keV (99.0%)



Considered accelerator

TrueBeam by Varian

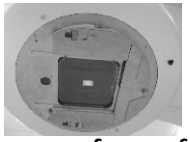
10 therapeutic beams

6 electron beams:
6 MeV
9 MeV
12 MeV
15 MeV
18 MeV
22 MeV

4 X-ray beams:
6 MV
10 MV FFF
15 MV
20 MV

These beams produce nontherapeutic radiation:
neutrons
gamma-rays
β radiation

Characterization of slowed down neutron field in vicinity of medical linac

model	beam	measurement locations	radiation field	Φ_{ther} / D_{max} [$cm^{-2}Gy^{-1}$]	Φ_{res} / D_{max} [$cm^{-2}Gy^{-1}$]	reference
TrueBeam	20 MV X-rays	 on surface of accelerator window	10cm x 10cm	3.1×10^6	2.0×10^6	1) Konefał *et al* 2015
	15 MV X-rays			1.1×10^6	6.7×10^5	
	10 FFF MV X-rays			7.1×10^4	4.1×10^4	
	22 MeV electrons			6.5×10^4	4.4×10^4	
CV 2300	20 MV X-rays	at isocenter	10cm x 10cm	1.3×10^6	1.0×10^6	2) Konefał *et al* 2005
	22 MeV electrons			1.1×10^4	2.1×10^4	
CV 21EX	15 MV X-rays	at isocenter	10cm x 10cm	1.97×10^5	-	3) Wen-Shan Liu *et all* 2011
	10 MV X-rays			1.46×10^4	-	

Φ_{ther}, Φ_{res} - thermal, resonance neutron fluence

D_{max} - the therapeutic maximum dose measured with the use of PTW 23343 ionization chamber in water phantom according to the recommendation of TRS-398.

IAEA TRS-398 2000 Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water. International Atomic Energy Agency, Vienna.

1) A. Konefał, A. Orlef, M. Bieniasiewicz., 2016. Measurements of neutron radiation and induced radioactivity for the new medical linear accelerator, the Varian TrueBeam. Radiation Measurements, 86, 8-15.

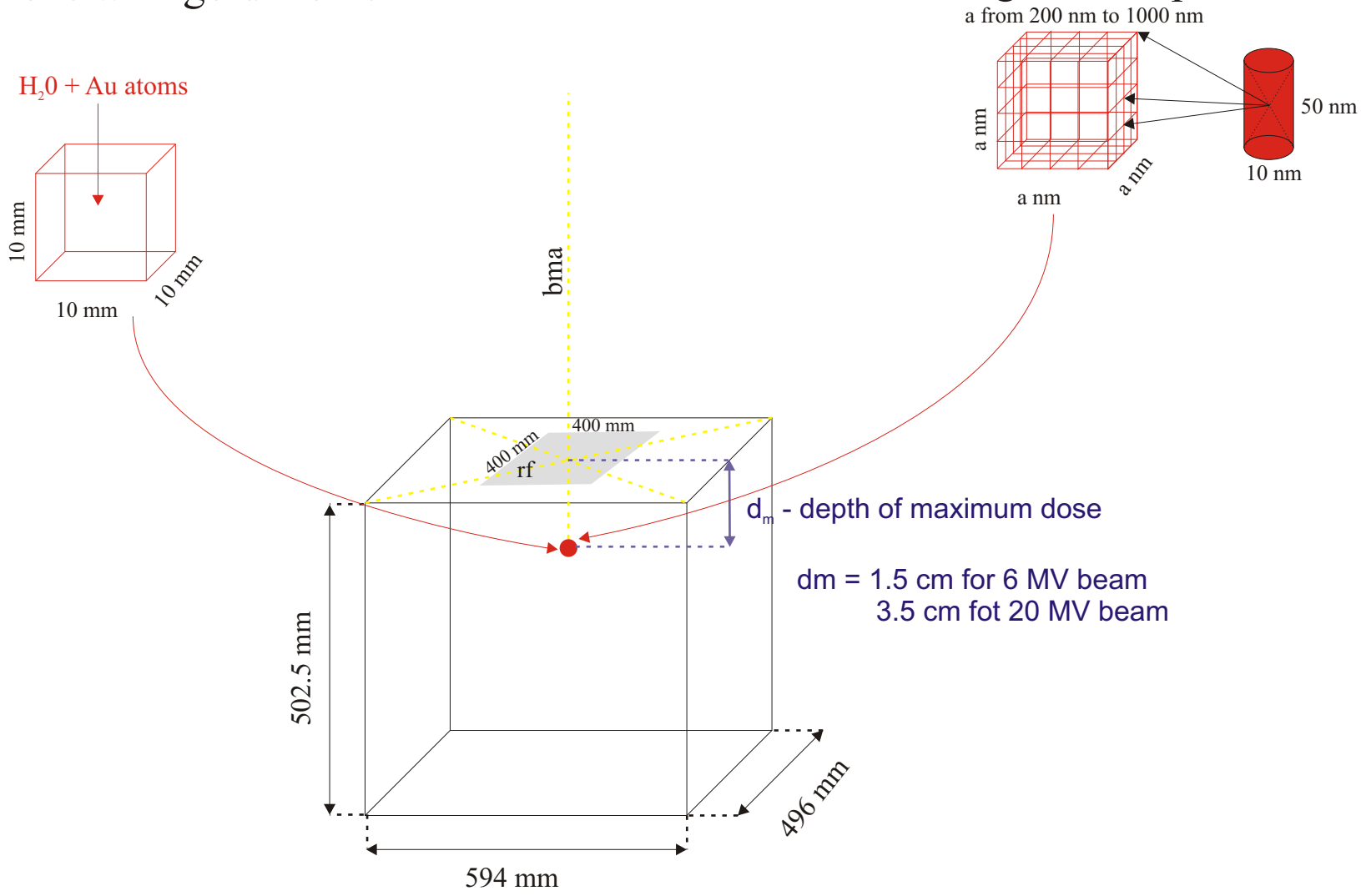
2) Konefał, A., Dybek, M., Zipper, W., Łobodziec, W., Szczucka, K., 2005. Thermal and epithermal neutrons in the vicinity of the Primus Siemens biomedical accelerator. Nukleonika 50, 73–81.

3) Wen-Shan Liu, Sheng-PinChanglai, Lung-Kwang Pan, Hsien-Chun Tseng, Chien-Yi Chen, 2011. Thermal neutron fluence in a treatment room with a Varian linear accelerator at a medical university hospital. Radiation Physics and Chemistry 80, 917–922.

Method

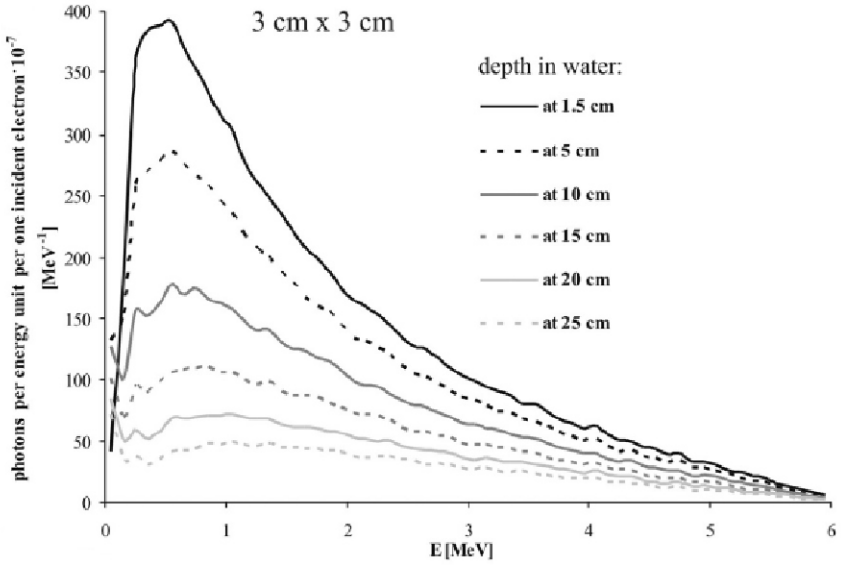
Simultions with gold atoms

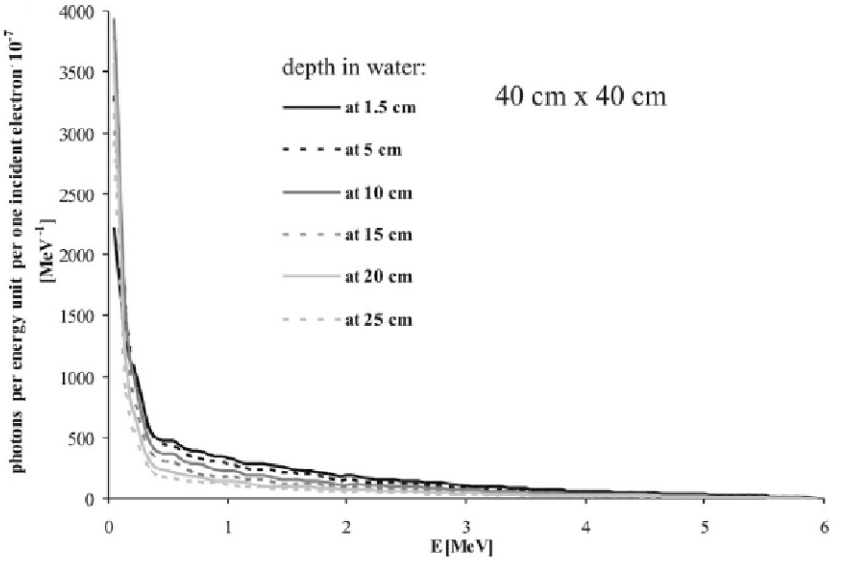
Simulations with gold nanoparticles

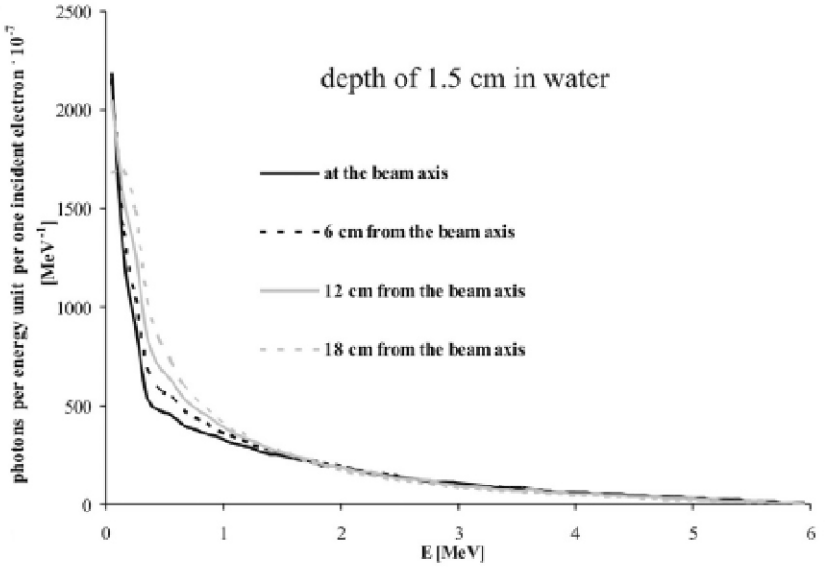


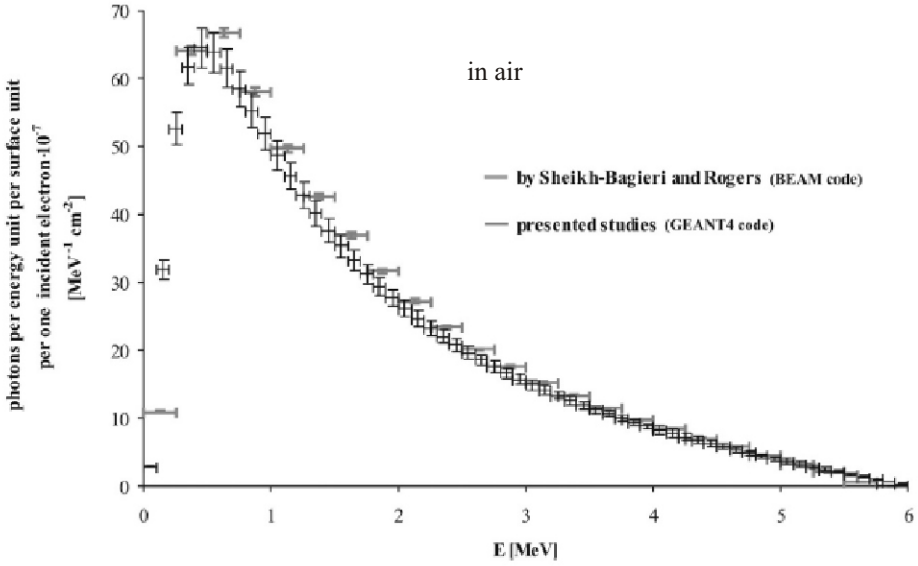
Spectra of therapeutic beams

A. Konefał et al. Radiation Measurements 72 (2015) 12-22









Used software

Version of code:

1. GEANT4.9.2.p02 + CLHEP 2.0.4.2 + g++ gcc 4.6, GNUMake
2. GEANT4.10.1.p01 + g++ gcc 4.6, Cmake
3. GEANT4.10.3.p03 + g++ gcc 4.6, Cmake

Operating system:

1. Mandriva 2009 PowerPack
2. Ubuntu 12.04

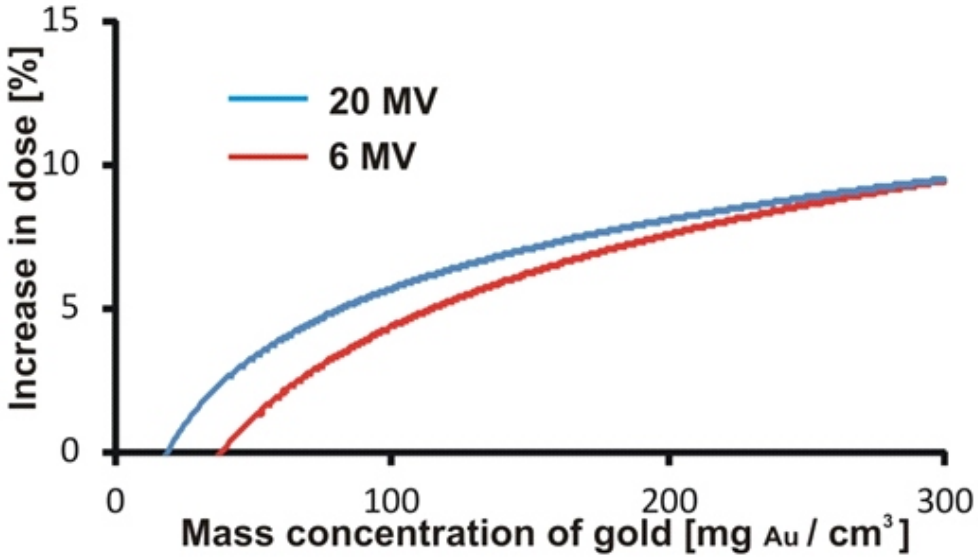
Used hardware

3 computers with 4-core 3 GHz processors
in Department of Nuclear Physics and Its Application,
Institute of Physics, University of Silesia in Katowice

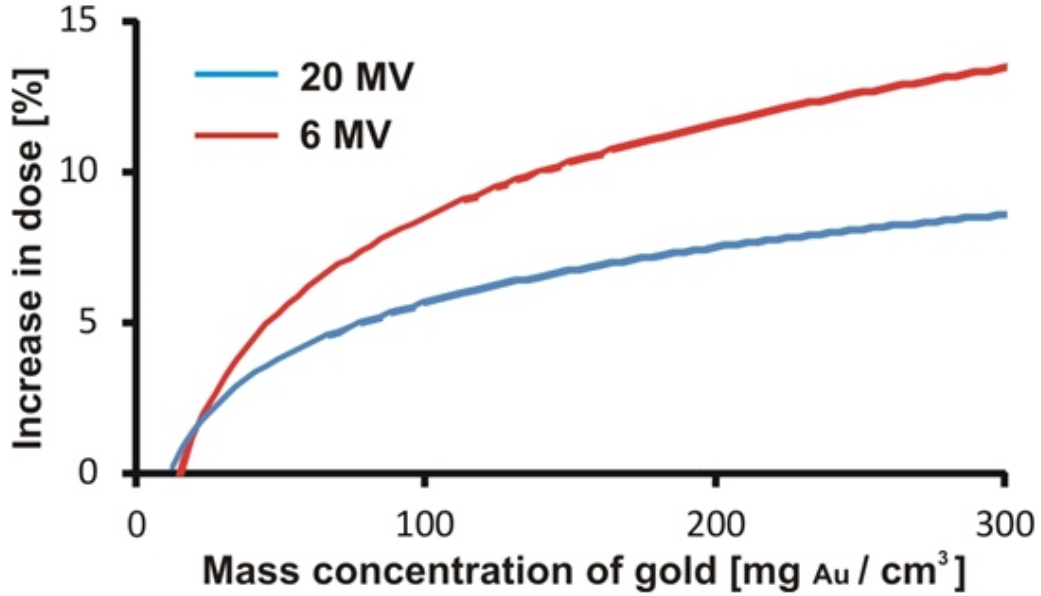
available application of PL-GRID

PL-Grid Infrastructure is a polish scientific community computer grid based on computer clusters, enabling research in various domains of e-Science. This infrastructure supports scientific investigations applying the advanced computer simulations. It provides convenient access to distributed computing resources.

Results

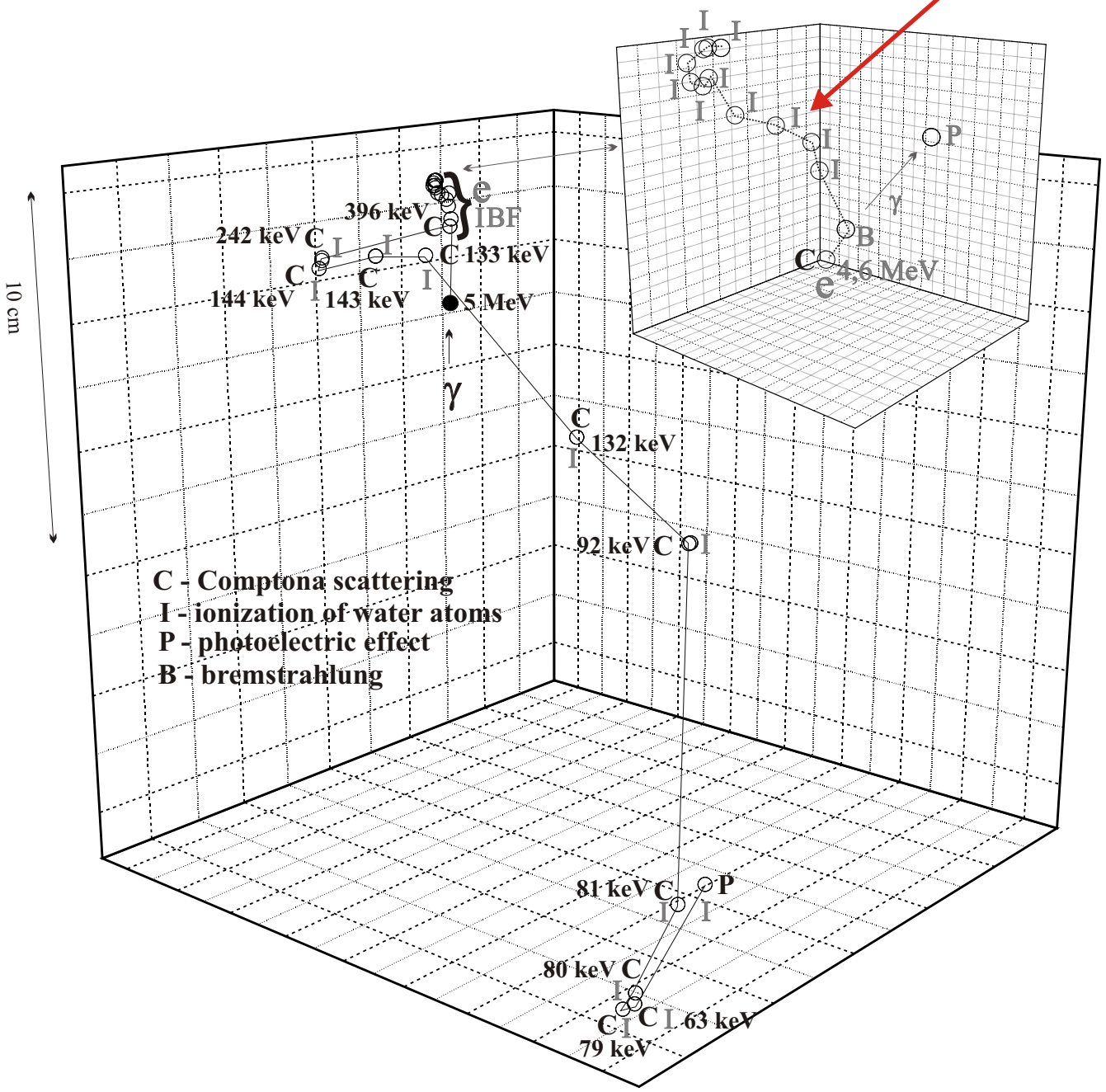


Increase of the dose absorbed in water in the target volume versus the mass concentration of gold in the irradiated medium for the case with the gold atoms.



Increase of the dose absorbed in water in the target volume versus the mass concentration of gold in the irradiated medium for the case with the large gold nanoparticles.

Explanation



Track of photon with energy of 5 MeV

Conclusions

The performed study indicates that

1) the use of the relatively large gold nanoparticles can limit the increase of the absorbed dose in the target volume,

2) the dose enhancement for the high-energy photons depends not only on the energy spectrum of the beams but also on the sizes of the gold nanoparticles,

3) the use of large agglomeration of gold atoms as a radiosensitizer is not profitable for the dose enhancement in teleradiotherapy realized by the 20 MV X-ray beam.


Thank You
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