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A Monte Carlo simulation study on the secondary neutron dose in passive proton therapy

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HIGHLIGHTS

- Passive scattering method in proton therapy has the potential for generating secondary particles, especially neutrons.
- Effect of using the passive method for different primary proton energies on the dose to the tissue is investigated.
- Effect of the presence of high-Z and low-Z materials in RM wheels is studied.
- The results are compared with those of the pencil beam scanning method

ABSTRACT

Among the approaches commonly used to extend the sharp peak of the deposited dose in proton therapy, passive scattering is widely used and also is of concern because of the potential for generating secondary particles, especially neutrons, which can damage the non-target healthy tissues. The present simulation-based study investigates the effect of using the passive method for different primary proton energies on the dose delivered to the tissue compared with those of the pencil beam scanning method. The results show that the generation of secondary neutrons strongly depends on the material used in the beam design. Also, it was found that the passive method would lead to the physical neutron dose higher than that of the beam scanning method for various primary proton energies.

KEYWORDS

Proton therapy
Passive method
Pencil Beam Scanning (PBS)
Secondary neutrons
Monte Carlo Simulations

HISTORY

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1 Introduction

Proton therapy is one of the most effective methods in the treatment of various tumors, especially in the case that the tumor is located near a sensitive organ of the patient's body which is due to the Bragg curve and its sharp peak following the interaction of protons in the tissue. This peak is too sharp with an abrupt fall-off and therfore is limited to a small volume in the target. In order to expand this area0 and cover the actual volume of the tumor, there are two general methods. In the first method, known as pencil beam scanning (PBS), the protons directly enter the tissue and the beam position on the target can be controlled using magnetic fields or other mechanical motion techniques to spread the proton beam over the desired volume (Grevillot et al., 2011).

The second method, named passive scattering, is a technique in which the scattering and range-shifting materials spread the proton beam before entering the tissue. Among the several range modulation techniques used in proton therapy (Koehler et al., 1975; Kostjuchenko et al., 2001), utilizing absorbers with different thicknesses in the beam path to adjust the initial beam energy is of particular interest. In this method, by using an arrangement of materials with different thicknesses, known as range-modulator (RM) wheels, on the path of a single energy beam of the accelerator, a beam with different energies are generated. This arrangement can include low-Z materials (such as plastic and water) to reduce the energy of the beam, or materials as a scatterer (often high-Z materials) to scatter the beam to the desired dimension and spread it laterally. By adjusting the thickness of the wheel, which is placed on the path of the output beam of the accelerator, the whole target can be irradiated. The magnitude of the angles of each thickness on the wheel determines the contribution of the Bragg peak in the spread curve (Slopsema, 2018).

During the slowing-down process of protons in the tar-

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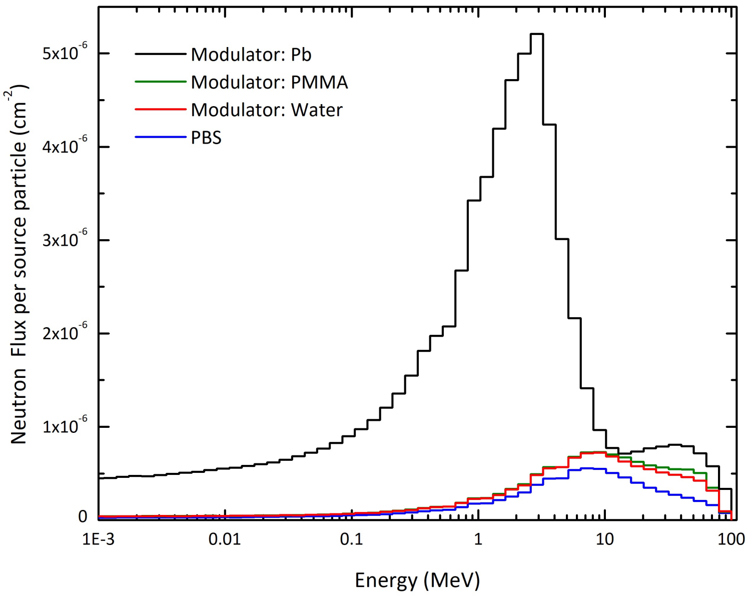

Figure 1: The neutron spectrum (per source particle) for both PBS and passive methods for the primary protons of 100 MeV in typical depth of 1 cm in the phantom.

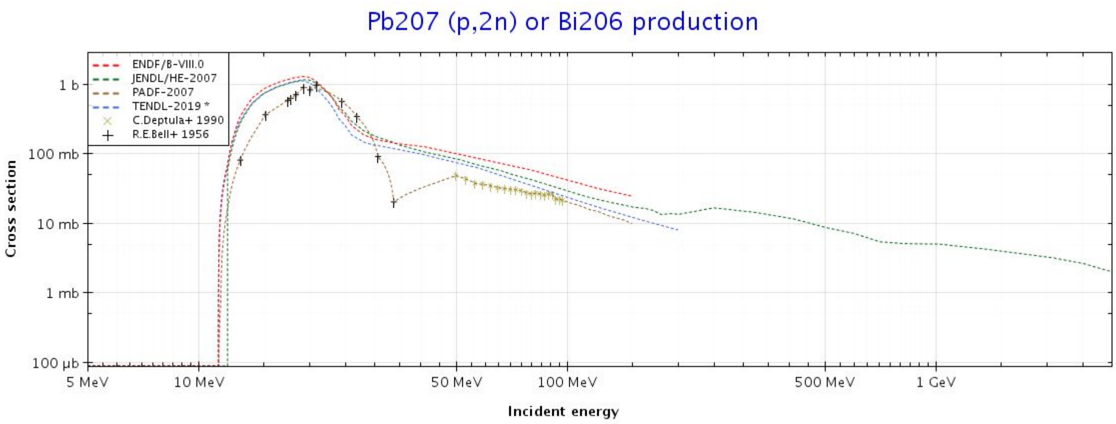

Figure 2: The Pb(p,2n) cross section. The data has been taken from JANIS database (`https://www.oecd-nea.org/janisweb/`).

get, there is a possibility that an incident proton may undergo a nonelastic nuclear interaction and generate secondary neutrons. According to the data reported by Janni (Janni, 1982), the nonelastic interaction cross section is zero near several MeV, and increases by increasing the proton energy. However, the threshold value depends on the target material. Though the passive method is widely used in proton therapy centers around the world (Olsen et al., 2007), it can be one of the main sources of secondary neutrons due to the nuclear interactions which occur during the proton beam passing through the RM wheel before entering the tissue. This raises concerns about the production of secondary particles and their effect on increasing unwanted doses to the healthy and non-target tissues.

The present study investigates the dose delivered to a phantom by secondary neutrons generated in the passive scattering method. The importance of the neutron dose arises from the fact that the relative biological effectiveness of neutrons is higher compared to photons and electrons. Owing that pre-clinical tests and simulation studies for radiotherapy are generally carried out using water or simplified materials (Rasouli et al., 2015), the simulated phantom has been filled with soft-tissue. The results are compared with those of the secondary neutrons in the PBS method. Also, the effect of the material used in the design of the RM wheel on the production of secondary neutrons has been studied.

2 Methods

To study the transport of protons through the target, either Monte Carlo simulations or analytical methods can be used. Though the latter is deterministic, it has been limited by the complicated equations derived by combining the physical processes occurring due to the interaction of protons, including the incident fluence of primary particles, the mass density and characteristics of the medium, the range of protons in the target, the initial energy, its

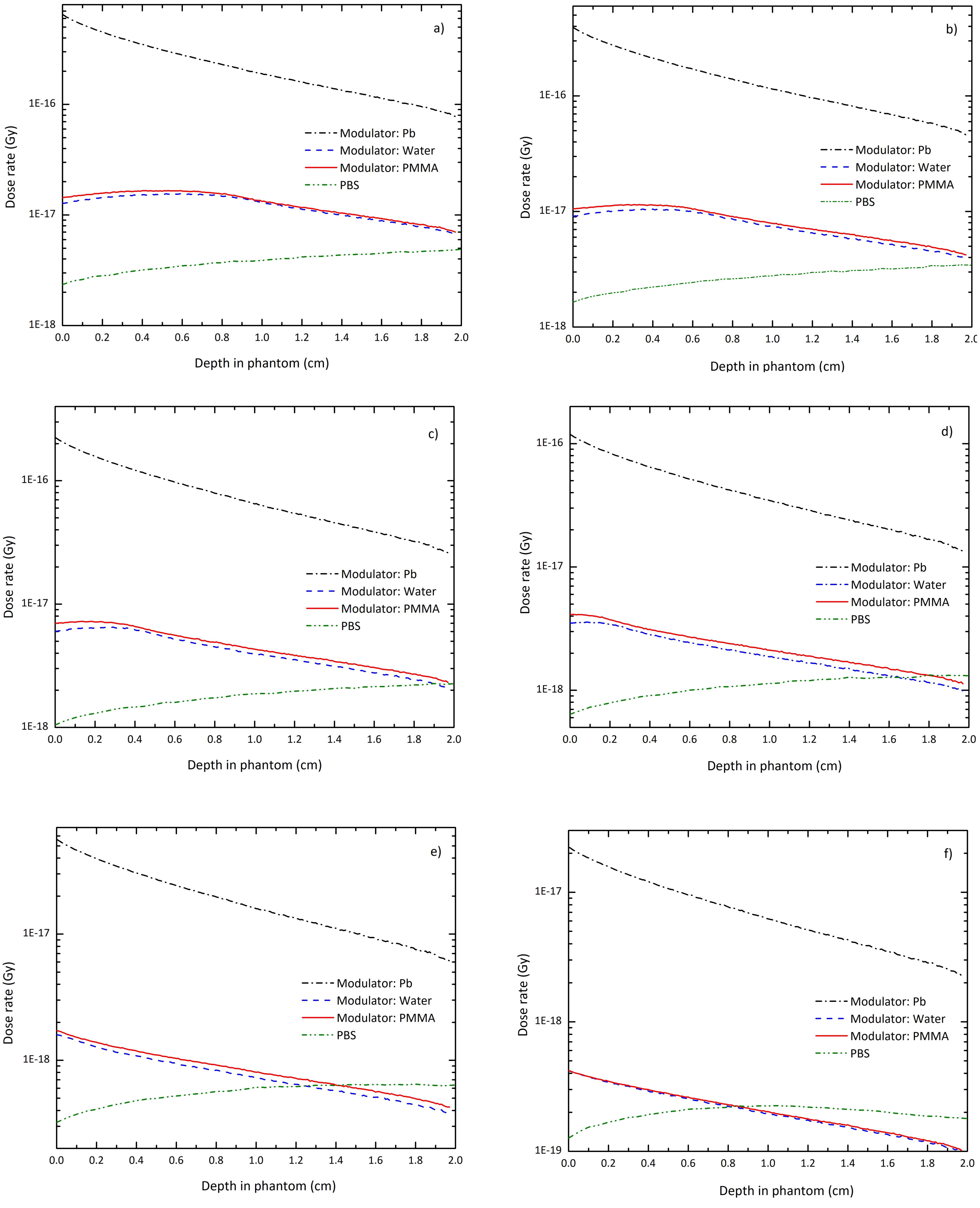

Figure 3: The physical dose delivered to the phantom due to the secondary neutrons for PBS and passive scattering method with different RM wheels. a) to e) panels are for primary protons of 100, 90, 80, 70, 60, and 50 MeV, respectively. The dose values have been calculated considering the number of generated neutrons per proton source particle.

spectrum and angular distribution, and the energy released due to the nuclear interactions [8, 9].

The Monte Carlo method is a well-known approach to perform calculations based on statistical methods. This method is especially useful for solving problems and predicting the consequences of situations involving several degrees of paired freedom. The Monte Carlo simulation, due to its high flexibility in solving various problems, is a suitable solution to study the behavior of radiation to the tissue and the dose delivered (Grevillot et al., 2011; Paganetti et al., 2004). In the present study, the MCNPX Monte Carlo code (version 2.6) (Pelowitz et al., 2008) has been used to simulate the geometries and particle transport in the medium. The number of histories have been chosen so that the statistical uncertainty is smaller than 1%.

A single-energy and forward direction proton beam with radius of 1 mm is considered as the output beam of a typical accelerator. To simulate the PBS method, the beam directly irradiates the target volume, which has been considered a cylindrical phantom of 5 cm radius of soft tissue. The dose values due to the protons as well as neutrons (as secondary particles produced by the interaction of protons with tissue) for the initial energies of 50 to 100 MeV, with 10 MeV steps, in the beam direction have been calculated.

In the passive method, the materials have been considered in the beam path to control the position of the Bragg peak in the depth of the phantom. In the realistic RM wheels, the absorber/scatterer thickness increases sequentially. By passing the proton beam through these layers of different thicknesses, the beams with different energies generate and therefore, the Bragg peak shifts into the depth of the phantom. Owing that the purpose of the present study is investigation of the effect of the presence of secondary neutrons on the dose delivered, a typical fixed thickness for RM wheel has been used. This process has been performed for three different types of RM wheels of PMMA plastic, water, and Pb with the tickness of 2 cm. The dosimetric results of the PBS method and the passive scattering method have been compared and discussed.

3 Results and discussion

Figure 1 shows the neutron spectrum in the typical depth of 1 cm in the phantom for both the PBS and passive scattering methods, irradiated with 100 MeV protons. The peak positions and the dominant energy of neutrons can be explained by the reaction cross section of protons with the target material; It was found that the energy of the irradiated protons in 1 cm depth of the phantom is about 21±0.7 MeV. Obviously, this energy is higher in the RM wheel before reaching the phantom. On the other hand, the Pb(p, n) reaction cross section reaches its maximum value for protons of about 20 MeV (Fig. 2). As a result, the secondary neutrons with energies less than the primary proton energies will be generated. As the energy spectrum of the neutrons (Fig. 1) shows, the neutrons belong to this energy interval. Strictly speaking, the spectrum of the generated neutrons can be explained by the main nuclear reaction and the primary energy of the protons.

Figure 3 shows the physical dose, which can be converted to effective dose by multipying an appropriate weighting factors, in each millimeter of the depth of the phantom in both the PBS and passive scattering methods for six various primary proton energies. In the passive method, three different materials for the RM wheel have been used. In both methods, the dose values have been calculated considering the initial number of neutrons entered the phantom. Strictly speaking, the dose values have been related to the number of generated neutrons per proton source particle. As the results show, in both methods, the neutron dose increases by increasing the proton energy. Also, in the PBS method, the dose delivered decreases compared with the passive scattering. Strictly speaking, in the entrance of the phantom, the dose delivered to the phantom for the RM wheels of Pb, PMMA, and water are about 13.44, 2.19, and 2.04 times larger than that of the PBS method for 100 MeV protons. These values reach 8.62, 1.4, and 1.4 times for 50 MeV protons.

However, the more interesting result is that these curves strongly depend on the material used in beam design, and the Pb-based RM wheels are responsible for generating secondary neutrons and undesired doses delivered to the phantom. As can be seen, the passive method generates more neutron doses, especially in the initial depths of the phantom.

Figures 4, 5, and 6 show the deviation between the neutron dose delivered to the depth of the phantom due to the PBS method from those due to the passive scattering with RM wheels of Pb, PMMA, and water, respectively. Various pimary energies have also been included in these figures.

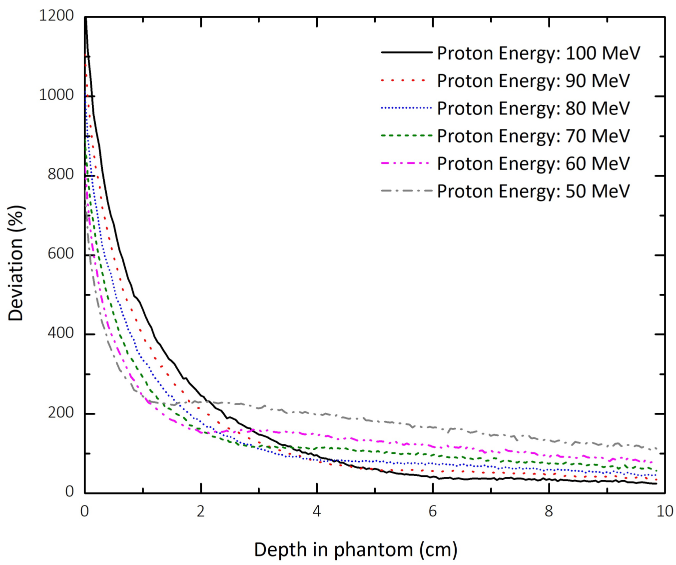

Figure 4: Deviation between the neutron dose delivered to the depth of the phantom for the PBS method and those due to the passive scattering with RM wheel of Pb for various primary energies.

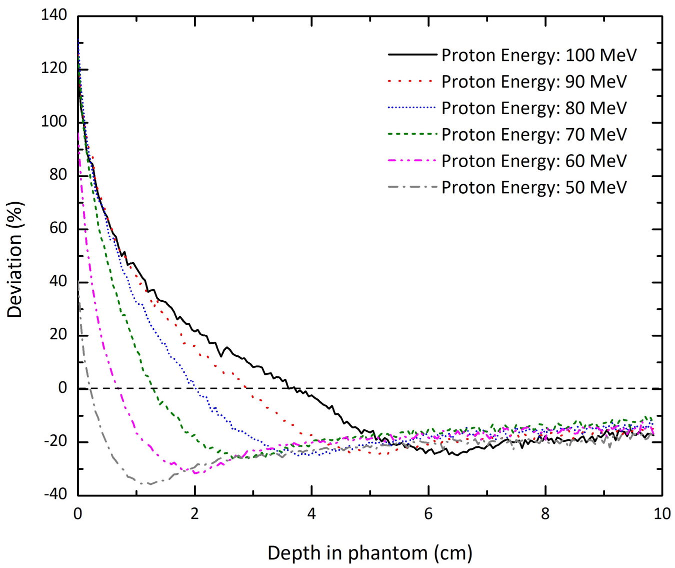

Figure 5: Deviation between the neutron dose delivered to the depth of the phantom for the PBS method and those due to the passive scattering with RM wheel of PMMA for various primary energies.

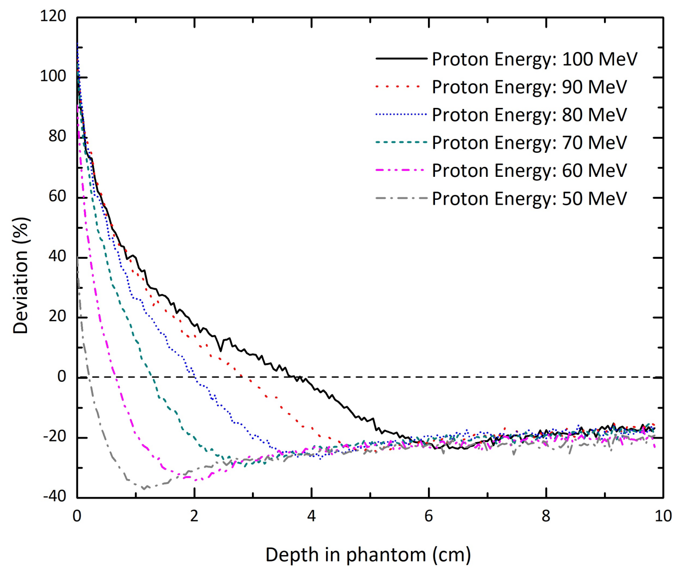

Figure 6: Deviation between the neutron dose delivered to the depth of the phantom for the PBS method and those due to the passive scattering with RM wheel of water for various primary energies.

To investigate the effect of material type, Fig. 7 compares these deviation for the three tested materials as RM wheel for the typical primary energy of 100 MeV. Obviously, the RM wheel of Pb generates larger values of the dose due to the secondary neutrons in the depth of the phantom.

4 Conclusions

The advantages of proton therapy over conventional radiotherapies include adjustable range, sharp peak and distal fall-off, acceptable penetration in tissue, and localized energy losshas made this method appropriate for treatment of tumors. Though the most current active proton therapy centers work based on the passive method, the presence of secondary particles, especially neutrons, can not be ignored. Obviousely, the phantom subjested to the proton radiation of passive method recieves higher neutron doses compared with the PBS method. The results show that for higher proton energies, this dose component is more important.

Also, it was found that the presence of high-Z materials in RM wheels leads to higher damage to the non-target tissue. However, these materials are vital to scatter the narrow beam and to spread the beam laterally in tissue. There should be a trade-off between using high-Z materials in the beam design and the unwanted dose to the tissue considering the limited values, i.e. the dose values recommended to prevent the healthy tissues from injuries during the radiation.

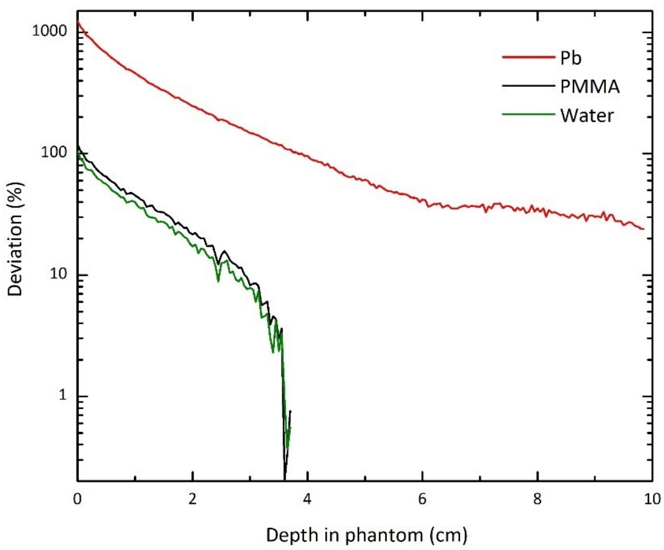

Figure 7: Deviation for the three tested materials as RM wheel for the primary energy of 100 MeV.

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