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Revisão cienciométrica dos fatores de escalonamento para profundidade e fluência de fantomas dosimétricos feitos em materiais plásticos

Scientiometric review of scaling factors for depth and fluency of dosimetric phantoms made of plastic materials

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RESUMO

Este artigo apresenta uma análise cienciométrica dos fatores de escala para profundidade (c_{pl}) e fluência (h_{pl}) em materiais termoplásticos utilizados em fantomas dosimétricos, com base em dados da Scopus, Web of Science e Science Direct (2015-2025). Dos 89 artigos identificados, 6 foram selecionados. Observou-se um aumento nas publicações nos períodos de 2015 a 2017, 2018 a 2020 e 2021 a 2023. O Irã liderou com 50% dos estudos, seguido por Brasil, Coreia do Sul e Grécia (16,67% cada). O material mais citado foi o RW3 (poliestireno com 2,1% ± 0,2% de TiO2, também conhecido por Goettingen White Water), presente em 50% dos artigos. Polimetilmetacrilato (PMMA), SP34 (poliestireno branco (C_8H_8) com pequena porcentagem de dióxido de titânio (TiO_2), Lucite (nome comercial para o plástico sintético polimetilmetacrilato) e PLA (ácido polilático) foram envolvidos em 16,67% dos estudos, cada. As densidades foram: PLA (1,240 g/cm³), PMMA (1,130 g/cm³), Lucite (1,190 g/cm³), RW3 e SP34 (1,045 g/cm³). A densidade eletrônica foi de 3,940 e 1,01 (el/cm³ × 10^{23}) para PLA e SP34, respectivamente. Os fatores de escalonamento c_{pl} e h_{pl} foram: PLA (0,946/1,050), PMMA (0,960/0,954), Lucite (0,941), RW3 (0,930/1,001) e SP34 (0,923/1,019). A análise cienciométrica auxilia na identificação de tendências e impactos, otimizando recursos em pesquisa oncológica e promovendo o desenvolvimento de técnicas mais eficazes e acessíveis para tratamento de tumores superficiais e dosimetria relativa.

Palavras-chave: Radioterapia. Fantoma. Fatores de Escalonamento. Dosimetria. Elétrons

ABSTRACT

This article presents a scientometric analysis of the scaling factors for depth (c_{pl}) and fluence (h_{pl}) in thermoplastic materials used in dosimetric phantoms, based on data from Scopus, Web of Science, and Science Direct (2015–2025). Out of the 89 identified articles, 6 were selected. An increase in publications was observed during the periods 2015–2017, 2018–2020 e 2021–2023. Iran led with 50% of the studies, followed by Brazil, South Korea, and Greece (16.67% each). The most cited material was RW3 (polystyrene with 2.1% ± 0.2% TiO_2, also know as Goettingen White Water), appearing in 50% of the articles. Polymethyl methacrylate (PMMA), SP34 (white polystyrene (C_8H_8) with a small percentage of titanium dioxide (TiO_2)), Lucite (a brand name for the synthetic plastic polymethyl methacrylate), and PLA (polylactic acid) were each addressed in 16.67% of the studies. The densities were as follows: PLA (1.240 g/cm³), PMMA (1.130 g/cm³), Lucite (1.190 g/cm³), RW3 and SP34 (1.045 g/cm³). The electron density was 3.940 and 1.01 (el/cm³ × 10^{23}) for PLA and SP34, respectively. The Hounsfield Unit (HU) value for PLA was 180±30. All studies were experimental, with one employing Monte Carlo (MC) simulation for validation. The scaling values for c_{pl} and h_{pl} were: PLA

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(0.946/1.050), PMMA (0.960/0.954), Lucite (0.941), RW3 (0.930/1.001), and SP34 (0.923/1.019). The scientometric analysis helps identify trends and impacts, optimizing resources in oncological research and promoting the development of more effective and accessible techniques for treating superficial tumors and relative dosimetry.

Keywords: Radiotherapy. Phantom. Scaling Factors. Dosimetry. Electrons.

1. INTRODUCTION

In contemporary dosimetric protocols, the absorbed dose to water is considered as the fundamental quantity for determining clinical beam characteristics in external radiation therapy. Water is the preferred reference medium over other materials (e.g., air) due to its physiological abundance and practical advantages, including reduced measurement uncertainty, the robustness of primary standards, and minimized correction factors (INTERNATIONAL ATOMIC ENERGY AGENCY, 2024, p. 27-32).

Despite its advantages, water-based dosimetry presents logistical challenges, particularly for routine beam constancy checks, which can be labor-intensive and time-consuming (DIAMANTOPOULOS et al., 2018, p. 1708-1714). For this reason, plastic phantoms are widely employed as water substitutes for daily dosimetric quality assurance (ROONEY et al., 2020, p. 15-26). However, accurate conversion of measured signals from these phantoms to the absorbed dose in water is crucial for ensuring measurement fidelity. Extensive research has been conducted on the water equivalence of solid phantoms, yet inherent uncertainties in these conversions may introduce potential inaccuracies. Recognizing this, the International Atomic Energy Agency (IAEA) and the American Association of Physicists in Medicine (AAPM) strongly discourage the use of non-water phantoms for reference dosimetry (DIAMANTOPOULOS et al., 2018, p. 1708-1714). When their use is necessary (e.g., for relative dosimetry), appropriate scaling factors must be applied to maintain dosimetric accuracy (INTERNATIONAL ATOMIC ENERGY AGENCY, 2024, p. 27-32; HUQ et al., 2001, p. 232-237).

In the photon dosimetry, the depth scaling factor c_{pl} is calculated based on the ratio between the electron density of water to that of the solid phantom. Since the well-characterized electron density of water, this factor can be calculated provided the phantom's chemical composition is known. The fluence scaling factor h_{pl} is then subsequently determined as the ratio of the dose measured at a reference depth in water (typically 10 cm) to the corresponding depth in the phantom after scaling. In contrast, electron dosimetry presents greater complexity in scaling factor determination. This process requires the acquisition of percentage depth dose curves for both water and the phantom medium, with reference depths established at each energy level to ensure accurate dosimetric calibration (PARTY, IPEM WORKING et al. 2003, p. 2929).

Since its inception in the 1980s, rapid prototyping has been widely applied across various domains. Recent advancements have facilitated the accessibility of three-dimensional (3D) printing technology, particularly in medical sciences. The versatility in design and material properties of thermoplastics has made this technology increasingly attractive to medical physics applications. Notably, 3D printing has been leveraged to address practical challenges in radiation therapy, including the fabrication of patient-specific boluses for external electron radiation therapy, the development of customized brachytherapy applicators, and the production of magnetic resonance imaging (MRI) compatible treatment templates. These innovations underscore the potential of 3D printing in advancing precision and efficiency in radiotherapy dosimetry and treatment delivery (PARK et al., 2016, p. e0168063; BURLESON et al., 2015, p. 166-178; SU et al., 2014, p. 194-211; AVILES et al., 2016, p. E622-E623; CUNHA et al., 2015, p. 246-253; DIAMANTOPOULOS et al., 2016, p. 208-209; VENEZIANI et al., 2016, p. 012088; PEREIRA et al., 2021, p. 109726).

In this context, scientometrics plays a crucial role in the quantitative analysis of scientific output, assessing parameters such as citation metrics and the impact of academic publications. These indicators enable the identification of the most widely applied techniques and those demonstrating the greatest efficacy in advancing scientific knowledge (IVANCHEVA, 2008, p. 47-56). Consequently, researchers and professionals in the field can strategically focus their efforts on the most promising interventions, thereby accelerating the development of innovative solutions.

This study aims to conduct a scientometric review of scientific literature regarding the main approaches, research trends, and existing gaps in depth scaling and fluence scaling factor determinations. The focus will be on models made from thermoplastic materials commonly used in 3D printing. By offering insights into the current state of research in this field, the study seeks to contribute to the refinement and optimization of therapeutic practices in radiotherapy.

2. THEORETICAL FRAMEWORK

An exploratory and review-based study was conducted (PIOVESAN et al., 1995, p. 318-325) with the purpose of deepening the understanding of the topic "scaling factors for depth and fluence in dosimetric phantoms manufactured using 3D printing" within the context of Medical Physics. This study was guided by a systematic review of scientific articles indexed in the Scopus (https://www.scopus.com/), Web of Science (https://www.webofscience.com/), and Science Direct (https://www.sciencedirect.com/) databases—platforms chosen for their broad coverage and the relevance of their publications in the field of Medical Physics. The research was carried out in March 2025, using the keywords "RADIOTHERAPY" and "PHANTOM" and "SCALING FACTORS" and "DOSIMETRY" and "ELECTRONS". To refine the results, filters were applied for the document type "Article" or “Review”, and the results were sorted by relevance.

The selected articles were analyzed and classified into eleven distinct categories: (i) publication period, covering studies published between March 2015 and March 2025; (ii) geographic location of the research, identifying the country where the study was conducted; (iii) number of materials investigated; (iv) determination of mass density; (v) determination of electron density; (vi) determination of Hounsfield Unit (HU); (vii) methodological approach adopted, indicating whether the study was experimental, theoretical, or hybrid; (viii) values of the scaling factors c_{pl} and h_{pl}; and (ix) verification of the experimental results through Monte Carlo (MC) simulations (ANDREO, 2018, p. 121, 2018).

Data collection for the scientometric analysis was carried out in two stages. Initially, a screening of the articles was conducted through the reading of their abstracts, with the aim of identifying those with potential relevance to the research. Subsequently, a full reading of the previously selected articles was performed in order to confirm their relevance and deepen the analysis.

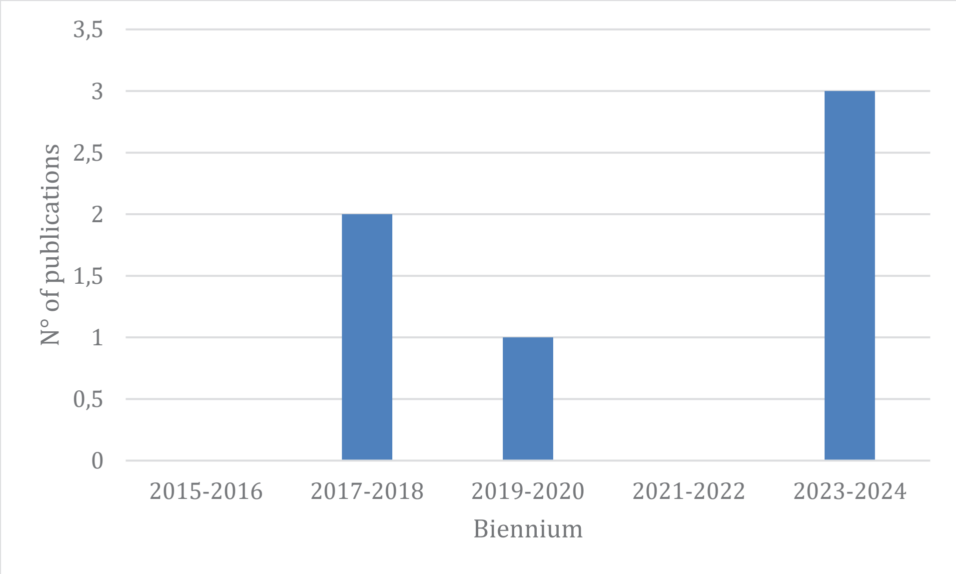
Scientific articles that did not provide abstracts or full texts in the consulted databases were excluded from the analysis. Studies without a direct and objective connection to the thematic scope were disregarded. Lastly, duplicate records retrieved from the search databases were excluded. This methodological rigor ensured that only the most relevant articles, directly related to the topic under investigation, were included in the analysis and discussion.

3. RESULTS AND DISCUSSION

3.1 Number of publications

The literature search identified 57 publications, distributed across the following platforms: Scopus (10 articles), Web of Science (12 articles), and ScienceDirect (35 articles). Studies that were not directly related to depth scaling factor c_{pl} or fluence scaling factor h_{pl} in materials with potential dosimetric applications in megavoltage electron beams used in radiotherapy were excluded from the analysis. Articles with incomplete, unavailable, or duplicate data across the databases consulted were also discarded. After rigorous application of these criteria, six articles were selected for the scientometric analysis. Figure 1 shows the number of articles published by triennium. Comparing the number of publications grouped into biennium (2015-2016, 2017-2018, 2019-2020, 2021-2022 and 2023-2024 excluding the 2025-2026 biennium, which is still ongoing). A growing trend was observed in the number of publications in the research field studied, albeit with large relative variations over time. Since the absolute number of publications per biennium is small, ranging from zero to three, the result in Graph 1 can be interpreted as the result of a niche and specialized research field. This is a highly specific subject area within radiation dosimetry and medical physics, often related to phantom design, MC simulation, or treatment planning system (TPS) calibration. Such niche areas are likely to attract a relatively small number of researchers, often rely on funding and resources that are not consistently available and may only gain temporary attention during certain technological or clinical developments. Because the topic isn't a mainstream research trend, publications depend heavily on individual research projects, master's or PhD theses, or limited-term grants. Once a project ends, publication output drops unless picked up by a new initiative (CARELLI, 1998, p. 265-278). It is also subject to occasional surges in publications (up to 2–3 in some years) that may correspond with the advent of 3D printing in radiotherapy, interest in new TPS algorithms or dosimetric verification protocols or even introduction of new materials or updated IAEA/AAPM protocols prompting comparative studies. These triggers lead to short bursts of research and publication, followed by years with little or no output. The high relative variability despite low absolute numbers is typical of under-researched, project-dependent areas. One or two active research groups or thesis projects in a given year can significantly affect the total, resulting in a pattern that looks "unstable" but simply reflects the scale and nature of the field (PAUL, 1991, p. 71-127), although as a whole, research involving general uses of 3D printing in radiotherapy has shown evident growth (ROONEY et al., 2020, p. 15-26).

Figure 1. Number of articles published according to the two-year period



Source: the authors, 2025

The database search yielded 57 articles, of which only 6 were included in this study due to the thematic inadequacy of the other 51 articles within the scope of the study. During the information survey, a significant number of publications were observed involving the use of plastic materials whose density tends to be equivalent to that of water (MCEWEN, et al., 2003, p. 1885; ŞAHMARAN, et al., 2022, p. 709-714). However, the use of materials that can be used in 3D printing may become increasingly relevant due to the clear advantages of rapid prototyping that becomes possible with this technology (SRINIVASAN et al., 2022, p. 110259).

In Figure 1, it was noted that, despite the relative increase in the number of publications over the years, the absolute increase is still small, with the biennium with the largest number of published studies being the one from 2023 to 2024. As there are several types of plastic materials that can be used in 3D printing of objects that can be used in electron radiotherapy, it is important to highlight the importance of the emergence of new studies that provide this data, i.e., scaling factors for common thermoplastics such as ABS, TPU, and PETG, for example.

There has been an increasing trend in the number of publications on scaling factors for plastic materials used in radiotherapy over the past 10 years. This is likely due to the importance of establishing a standardized method for determining these quantities with the advent of the Technical Report Series-398 (TRS-398). Furthermore, the growing popularity of 3D printing of thermoplastic materials may have contributed to the widespread use of PLA, ABS, TPU, and even PETG filaments, which are recyclable and therefore sustainable, and consequently, the increase in the number of publications.

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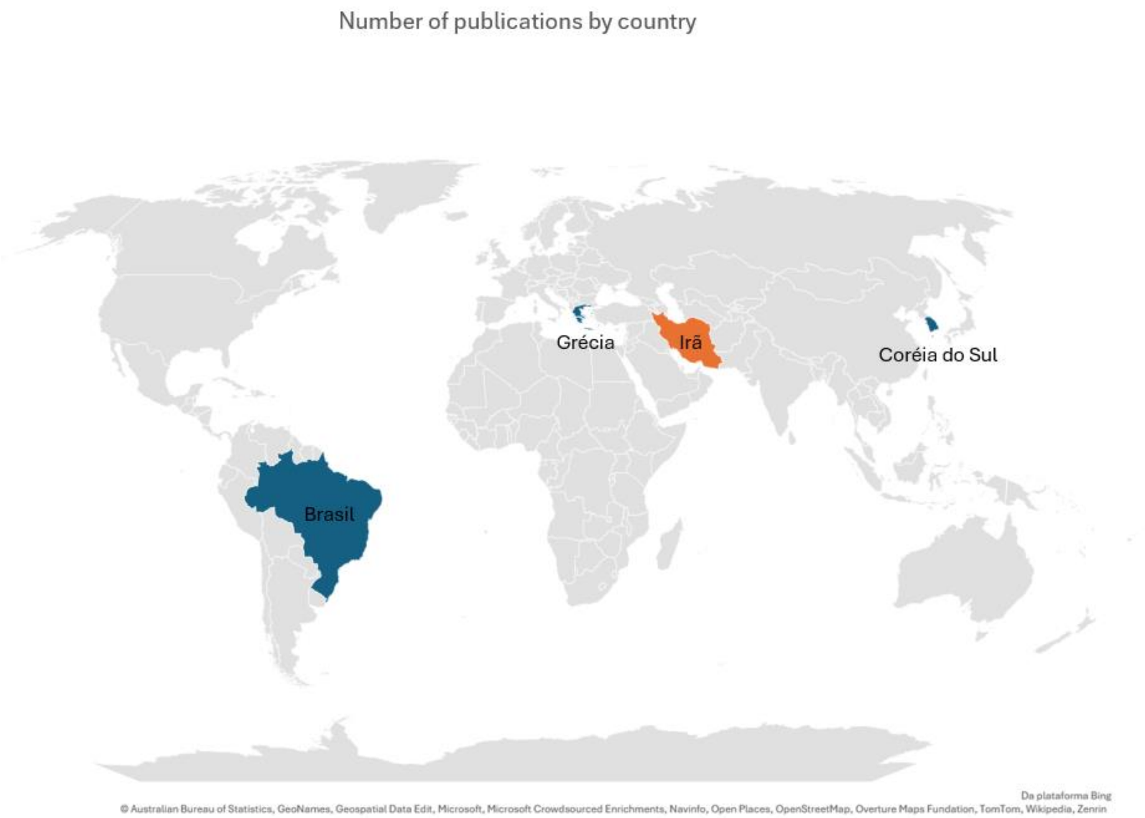
3.2 Distribution of articles produced by country

Figure 2 shows the distribution of articles produced by country. Iran was the country with the highest number of articles (n=3), accounting for 50.00% of published articles. Brazil, South Korea, and Greece followed in second place (n=1 each), accounting for 16.67% of the production individually, or 50.00% of the global production on the topic combined.

Figure 2. Scientific articles classified according to the location where the research was carried out.



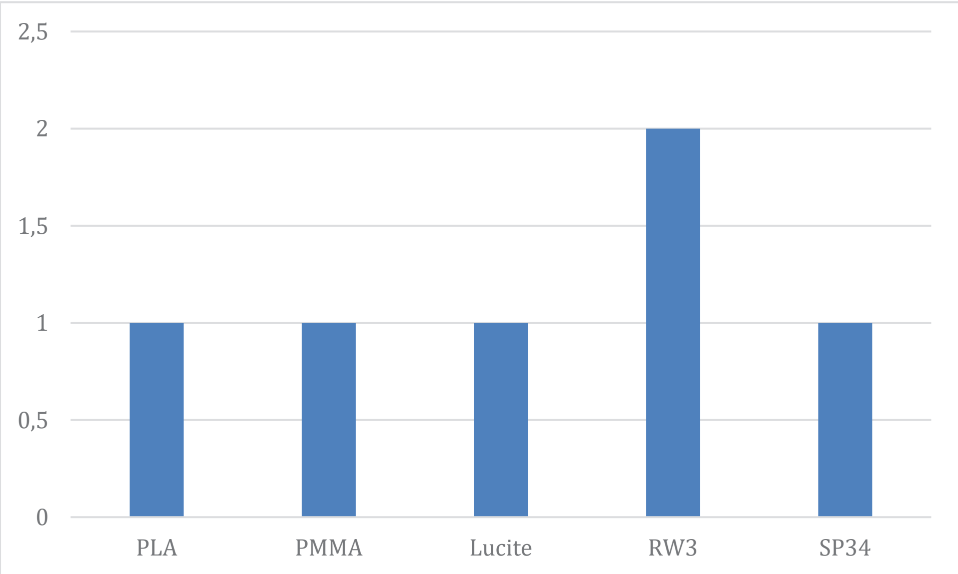
Source: the authors, 2025

This low absolute number of articles in the field reveals the apparent concentration of research in a single country, in this case, Iran. This concentration can be understood as natural due to the exponential increase in the number of publications involving ionizing radiation from this country in recent years (DAVARPANAH, 2012, p. 421-439). In addition to Iran, the other countries listed in Figure 2—Brazil, South Korea, and Greece—have demonstrated significant development in clinical applications of ionizing radiation (BARROS, pp. e-274889, 2024) and the production of radiopharmaceuticals (SOUZA, 2022), as well as in electricity generation (GUAL, 2023, p. 1-17).

3.3 Number of articles for each plastic researched

Regarding the number of materials whose c_{pl} and h_{pl} values were determined in the studies, data were collected on the most common materials found in the literature (Figure 3). The results of this analysis indicate that RW3 is the most frequently used material in this type of research, representing 28.57% of the publications (n=2). Next, PLA, PMMA, Lucite, and SP34 appear in 14.29% of the studies each. There appears to be no clear reason for the more frequent use of RW3 over other commercially available plastic phantoms such as PMMA, Lucite, and SP34, since they all have the same goal: to resemble water as closely as possible, primarily in terms of mass density, as well as other dosimetric impact parameters such as electron density and HU.

Figure 3. Number of articles for each material researched.

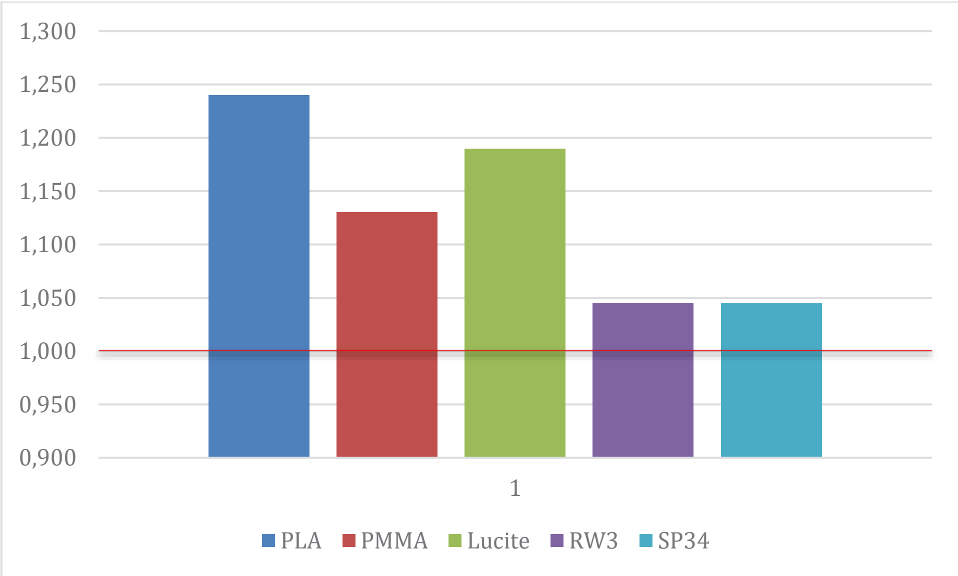


Source: the authors, 2025

It is important to highlight that among all the materials listed, only PLA is a thermoplastic used in 3D printing. The other materials are plastics considered water equivalent and have been widely used in relative dosimetry of megavoltage beams produced in radiotherapy for many decades. Their dosimetric parameters, such as c_{pl} and h_{pl}, are well known. These materials were developed by their manufacturers to be as water equivalent as possible, and there is extensive literature on their applications and dosimetric properties in specific articles (HUQ et al., 2001,

p. 232-237; MCEWEN, et al., 2003, p. 1885; ŞAHMARAN, et al., 2022, p. 709-714) as well as in international reference materials (INTERNATIONAL ATOMIC ENERGY AGENCY, 2024, p. 121).

Figure 4. Densities of the plastic materials used in the selected studies. The red line highlights the mass density of water by definition.



Source: the authors, 2025

3.4 Mass density of plastic materials

Figure 4 shows the mass densities of the plastic materials used in the studies selected for this scientometric review. The phantom manufactured in a 3D printer using PLA filament had a density of 1.240 g/cm3, and the other plastic materials (PMMA, Lucite, RW3, and SP34) had a density of 1.130, 1.190, 1.045, and 1.045 g/cm3, respectively. Again, it is worth noting that of all the materials listed, only PLA is a thermoplastic material used in 3D printing, and its density is significantly higher (approximately 14%) than that of the other materials proposed as water equivalents. In practical terms, this higher density does not preclude its use as a material for relative dosimetry or bolus production, for example, as long as its c_{pl} and h_{pl} scaling factors are well determined.

The densities of plastic materials were systematically higher than that of water, with water-equivalent materials having closer densities, while the material used in 3D printing, PLA, had a density 24% higher than unity (Figure 4). This is not necessarily a disadvantage, since all require their respective scaling factors and each has different molecular compositions and electronic densities not identical to those of water molecules, which leads to different probabilities of interaction of radiation with matter, namely: photoelectric effect, Compton scattering, pair production and annihilation, excitations, ionizations, etc. (OKUNO, 2016, p. 109-169).

3.5 Electron density, (HU), methodological approach and verification by MC simulations

Among all the selected articles, only two provided values for the electron density of the plastic materials used, with PLA having a value of 3.940 (el/cm3 x 1023) and SP34 1.01 (el/cm3 x 1023) (DIAMANTOPOULOS et al., 2018, p. 1708-1714; KIM et al., 2023, p. e0293191), one material used in 3D printing and the other used in the fabrication of commercial water-equivalent phantoms, respectively. This quantity is of interest in radiotherapy planning, as it is used to calculate dose deposition for various treatment techniques such as three-dimensional conformal radiotherapy (3DCRT), intensity-modulated radiotherapy (IMRT), volumetric intensity-modulated radiotherapy (VMAT), 2D superficial skin treatments, and radiosurgery, to name a few. Therefore, it would be interesting for new published articles to provide a wide range of data useful for clinical applications, not just c_{pl} and h_{pl} values.

A similar case occurred with the determination of HU, which is only included in one study among the selected ones, being 180±30 for PLA. Indeed, electron density and HU are related to the parameters of the imaging methods, e.g., the model of the computed tomography (CT) scanner used to acquire the clinical image (NAKAO et al., 2018, p. 271-275). Regarding this issue, only one article provided the HU information for the studied material (DIAMANTOPOULOS et al., 2018, p. 1708-1714).

All the selected studies were carried out experimentally, and one of them also included MC simulation to verify the results, which proved to be compatible within the margin of uncertainty of the tests performed (DIAMANTOPOULOS et al., 2018, p. 1708-1714). There are theoretical studies that use MC simulation to determine the ionization curves for materials used in 3D printing, such as PLA, ABS, and TPU (DIAZ-MERCHAN, 2023, p. 110908), from which it is possible to determine the c_{pl} and h_{pl} values based on the formalism presented in TRS-398. In his 2023 study, Diaz-Merchant also analyzed the influence of different geometric patterns in 3D printing. However, it is still interesting to characterize other materials to analyze their physical properties, such as mass density, electron density, ease of 3D printing, the ability to contain fewer air spaces within printed objects, which materials present less waste due to printing failures, which are less susceptible to part deformation, and which materials are affordable and accessible in various regions of the world.

There is a need for new articles that are comprehensive in terms of including values for mass density, electron density, HU, etc. These comprehensive studies are interesting, as it is necessary to understand all the main dosimetric characteristics of materials so that published studies have a broader scope for theoretical or clinical applications. Determining HU for various materials is not uncommon, but it is rare among studies whose main objective is to determine scaling factors for plastic materials used for various purposes in radiotherapy. It is interesting to characterize other materials to analyze their physical properties, such as mass density, electron density, ease of 3D printing, ability to contain fewer air spaces after printing, fewer parts breakages during production, exhibit a lower tendency to develop deformities, and ensure they are affordable and accessible in various regions.

3.6 Depth c_{pl} and fluence h_{pl} scaling factors

Table 1 presents the c_{pl} and h_{pl} values extracted from the six studies selected in this scientometric review. All c_{pl} values obtained were less than one, that is, lower than the reference value measured in water (INTERNATIONAL ATOMIC ENERGY AGENCY, 2024, p. 120-122), indicating that these materials are less dense than water or have a lower attenuation capacity for incident beams when compared to water. The h_{pl} values for plastic materials were all very close to one, the value that represents the reference in water, with the exception of Lucite, for which the value was not presented. Three of them, PLA, RW3, and SP34, were greater than one, the reference value measured in water, and one of them, PMMA, was below this value, indicating that the h_{pl} value presents little variability depending on the density of the plastic materials constituting the phantoms. Table 1 also shows that most studies were performed using commercial plates with an area of 30 x 30 cm², while the study using 3D printing was limited to a maximum area of 15 x 15 cm². This size is not ideal, as this design does not comply with TRS-398 guidelines, which recommend that phantoms extend laterally by at least 5 cm beyond the field edges at the depth of measurement—thus ensuring full lateral scatter conditions for a 10 x 10 cm² radiation field. This careful adherence to protocol enhances the reliability of the scaling factor determination and the dosimetric relevance of the printed materials. According to data in Table 1, this criterion is generally met when using commercial water-equivalent plates, but it may encounter limitations when used for 3D printing. Depending on the model used, the phantom size may be restricted to the maximum size that can be produced within the printer or may suffer from warping effects for relatively large objects. Therefore, it is clear that further studies are needed to systematically determine c_{pl} and h_{pl} values for other materials used in 3D printing.

Table 1: Scaling factor values for depth and fluence, and phantom dimensions for various materials.

Material	c_{pl}	h_{pl}	Dimensões (cm^2)	Autor
PLA	0,946	1,050	15x15	Diamantopoulos et al., 2022
PMMA	0,960	0,954	---	Baghani et al., 2020
Lucite	0,941	---	30x30	Nascimento et al., 2018
RW3	0,930	1,001	30x30	Baghani et al., 2024
SP34	0,923	1,019	30 x30	Kim et al., 2023

Source: prepared by the authors, 2025

In the literature, there are few studies whose primary objective is to determine the c_{pl} and h_{pl} scaling factors other than PLA (Figure 3) for 3D printing materials. These involve the use of materials whose density attempts to simulate that of water and are part of dosimetric plate sets sold by established suppliers in the field of Medical Physics.

4. FINAL CONSIDERATIONS

This review underscores the central role of water as the reference medium in contemporary dosimetric protocols due to its physiological relevance and measurement reliability. However, practical limitations associated with water-based dosimetry, particularly in routine clinical settings, have driven the widespread use of solid phantoms. While these alternatives offer logistical advantages, they necessitate precise scaling to maintain dosimetric accuracy, particularly for photon and electron beams. The advent of 3D printing has introduced new opportunities for customizing dosimetric tools using thermoplastic materials, offering both design flexibility and clinical utility. By integrating scientometric analysis into this evolving field, researchers can better understand the impact and development of scaling methodologies, helping to identify high-impact studies and materials with the greatest potential for clinical adoption. Ultimately, this synthesis of dosimetric science, material innovation, and scientometric evaluation serves to support the ongoing refinement of radiotherapy practices, promoting more accurate and personalized treatment delivery.

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