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TECHNICAL PAPER

Verification of the Elekta Monaco TPS Monte Carlo in modelling radiation transmission through metals in a water equivalent phantom

Kurt Byrnes[1] · Andriana Ford[1] · Nick Bennie[1]

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Abstract

Many studies have performed dosimetric studies using various metal implants however these are difficult to translate to other implants of a different geometry or material (Rijken and Colyer, J Appl Clin Med Phys 18:5:301–306, 2017; Ade and du Plessis, J Appl Clin Med Phys 18:5:162–173, 2017; Prabhakar et al. Rep Pract Oncol Radiother 18:209–213, 2013; Ng et al. Rep Pract Oncol Radiother 20:273–277, 2015; Reft et al. Med Phys 30:1162–1182, 2003; Sasaki et al., Nihon Hoshasen Gijutsu Gakkai Zasshi 72(9):735–745, 2016). In this study, the ability of the Monaco Monte Carlo algorithm (Elekta AB, Stockholm, Sweden) to model radiation transport through different types of metals was evaluated. Investigation of the capabilities and limitations of the algorithm is required for the potential use of Monaco for planning radiotherapy treatments when avoidance of metal implants is clinically undesirable. A MapCHECK 2 diode array (Sun Nuclear Corp, Melbourne, USA) and a PTW 30013 Farmer chamber was used to measure the dose at depth, downstream of 1 cm × 5 cm × 5 cm metal blocks of three known compositions; stainless steel, aluminium and MCP96. The setup was imaged using a CT scanner and imported into the Monaco TPS where the beam arrangement was replicated. The density of the metals was overridden using the known electron density of each (IMPAC Medical Systems Inc, Monaco dose calculation technical reference. IMPAC Medical Systems, Sunnydale, CA, 2013). The differences between the dose measured using the ion chamber and calculated using Monaco downstream of the 1 cm metal blocks were respectively: − 1.2%, − 2.2% and 9.5% when irradiated using a 6 MV beam, and − 0.9%, − 1.3% and 14%, when irradiated using a 15 MV beam. This was then repeated using 2 cm and 3 cm of each metal type giving similar results for aluminium and stainless steel and increased discrepancy for MCP96. Discrepancies between treatment planning software and measurements at depth have been shown to give uncertainties between 5 and 23% in previous studies (Rijken and Colyer, J Appl Clin Med Phys 18:5:301–306, 2017; Ade and du Plessis, J Appl Clin Med Phys 18:5:162–173, 2017; Prabhakar et al. Rep Pract Oncol Radiother 18:209–213, 2013; Ng et al. Rep Pract Oncol Radiother 20:273–277, 2015; Reft et al. Med Phys 30:1162–1182, 2003; Sasaki et al., Nihon Hoshasen Gijutsu Gakkai Zasshi 72(9):735–745, 2016). This study uses basic shapes providing results that remove the uncertainties in geometry and can therefore be applied to any shape. This will help determine whether errors in dose calculations are due to the TPS particle transport algorithms or due to other effects, such as inaccurate contouring or incorrect densities. Thus giving the planner an additional degree of freedom in their planning and decision making process.

Keywords Monaco · Monte Carlo · MCP96 · Metals · Hip prosthetics

Introduction

In recent years, the use of Monte Carlo (MC) dose calculation algorithms within commercial radiation therapy treatment planning systems (TPS) have become more prevalent. Commonly used TPS including Monaco, Eclipse, Pinnacle and Raystation all utilise Monte Carlo. This has led to a higher degree of confidence in the ability of the TPS to calculate dose within a patient, especially in heterogeneous mediums, high dose gradient regions and treatments

✉ Kurt Byrnes
Kurt.Byrnes@health.qld.gov.au

Andriana Ford
Andriana.Ford@health.nsw.gov.au

Nick Bennie
Nick.Bennie@health.nsw.gov.au

[1] NCCI, Lismore Base Hospital, Northern NSW Local Health District, Lismore, NSW 2480, Australia

involving implants. There is still however mistrust in the ability of commercial TPS to calculate dose within fields that pass through a high density metal implant [1–5]. This lack of trust is reasonable and understandable due to the evidence presented in papers that investigate the ability of TPS algorithms to perform such calculations [1–4, 6, 7]. Most current TPS algorithms that utilise Monte Carlo have not been adequately critiqued enough to make this judgement. This uncertainty can be seen in clinical protocols and international recommendations [4] regardless of the fact that the most common TPS Monte Carlo systems claim to support the use of high density metals and include documentation on how such metals will be treated [8–10].

By better understanding the uncertainties involved, the planner gains an additional degree of freedom in their decision making, allowing for better optimization of both forward and inverse planning techniques resulting in improved dose to target regions while sparing organs at risk. This is achieved by using an experimental setup representative of the distances, thicknesses and materials in a patient with a metal hip prosthetic. Indicating the error caused by Monaco to the dose delivered to organs at risk and targets which will assist planners and physicists in their decision making process.

Many studies have performed dosimetric studies using various metal implants however these are difficult to translate to other implants of a different geometry or material [1–4, 6, 7]. This study compared one of the most commonly used TPS, Monaco 5.11, to dose measurements performed on a beam matched linac. The composition of a patient's implant is usually unknown and this study does not attempt to give results for all available materials. This study aims to be a spot check of three metal types in order to validate the Monaco Monte Carlo algorithm. The accuracy of Monaco can potentially be assumed for similar metal types, or the methodology outlined in this study can be repeated for other common metals such as titanium or Cobalt Chromium alloys.

Discrepancies between modern TPS and measurements at depth have been shown to give uncertainties between 5 and 23% in previous papers [1–4, 6, 7]. This study uses basic shapes providing results that remove the uncertainties in geometry and can therefore be applied to any shape. This will help determine whether errors in dose calculations are due to the TPS particle transport algorithms or due to other effects, such as inaccurate contouring or incorrect assignment of RED (relative electron density). Contributions of each effect will have to be considered as a whole by the planning team.

Methods and materials

In order to evaluate the ability of the Monaco monte carlo algorithm to calculate photon transport through metals, measurements were taken within a phantom containing metal blocks. This setup was replicated in Monaco and the dose at depth compared to the measured values.

Three types of metal blocks were used Aluminium, Stainless Steel and MCP96. These were chosen to represent low density, high density and unrealistically high density materials respectively. The MPC96 blocks were fabricated in house. MCP96 is a metal very similar to Cerrobend in composition and use. Table 1 shows the physical characteristics of each metal.

The exact density and electron density of each block is unknown as the chemical composition is given as ranges. For the purposes of this experiment the physical density values were taken from the Monaco dose calculation technical reference which were in agreement with those used in other studies [1, 10]. Relative electron density was initially calculated using Eq. 1 [2, 11].

$$RED = \frac{\rho_m N_A \left(\frac{Z}{A}\right)}{\rho_e(\mathrm{H_2O})} \tag{1}$$

Since Monaco only allows the user to override RED and not mass density, Monaco calculates the physical density to be used in calculations using Eq. 2 [10].

$$\mathrm{RED} = 0.85\rho_m + 0.15 \tag{2}$$

Equation 2 is only valid for $\mathrm{RED} \geq 1$, different equations are used for $\mathrm{RED} < 1$ [10]. This method of determining mass density is designed to allow the MC algorithm to accurately model radiation transmission. However, the implication of this being that dose deposition accuracy can be degraded within materials with a physical density greater than 3 g/cm^3 [10].

Table 1 Physical characteristics of the three metal types used

Metal	Aluminium (Grade 6060-T5)	Stainless steel (Grade 304)	MCP96
Mass density (g/cm^3)	2.76	7.87	9.74
RED (Eq. 1)	2.4	6.6	7.11
RED (Eq. 2)	2.5	6.84	8.43
Composition	> 98% Al	18–20% Cr	15.5% SN
		8–10.5% Ni	32% Pb
		< 2% Mn	52.5% Bi
		Balance Fe	

Calculations for point dose were performed using both methods of RED determination. With both REDs shown in Table 1.

Dealing with phantoms involving metals, especially high density metals, involves additional uncertainties due to CT artefacts, inaccurate CT to ED conversion and contouring. All of these uncertainties needed to be removed in order to isolate any error caused by the MC algorithm. This was accomplished by scanning a 5 cm × 5 cm piece of cardboard as a surrogate for the piece of metal. The phantom setup was scanned, as shown in Fig. 1 using a Siemens Somatom Sensation CT scanner. The metal blocks were then later contoured in Monaco using the known dimensions and electron densities.

In the TPS a 10 cm × 10 cm 300 MU field was added for both 6X and 15X (TPR 20, 10 of 0.681 and 0.758 respectively). The phantom setup is as shown in Fig. 2, with distances chosen to approximately represent the depths involved with a prostate patient receiving lateral beam treatment through metal hips.

The metal block was submerged in the water filled container which was then placed on 1 cm of bolus, and 3 cm of Plastic Water (CIRS, Norfolk, VA, USA). The bolus was included to minimise the air gap between the plastic water container and the rest of the phantom.

The MapCHECK 2 (Sun Nuclear Corp., Melbourne, Fl, USA) was placed at the position identified in Fig. 1. This setup was similar to the setup chosen by Rijken et al. [6]. A 10 cm × 10 cm field was measured using the MapCHECK 2 for each metal type using 6 and 15 MV photons.

This was repeated for each metal type using additional 1 cm × 5 cm × 5 cm blocks to make the total metal thickness 2 cm and 3 cm. Multiple thicknesses were used to represent the different likely thicknesses of metal used in hip prosthetics. The depths of water above the depth of measurement were chosen to be representative of the depth of the metal hip and prostate respectively.

Measurements were then taken using a Farmer ion chamber (PTW30013) on the central axis at the same measurement depth. These values were corrected for any deviation in linac output or setup factors by correcting for the difference in dose between planned and measured when no metal blocks were in place. This was done using Eq. 3.

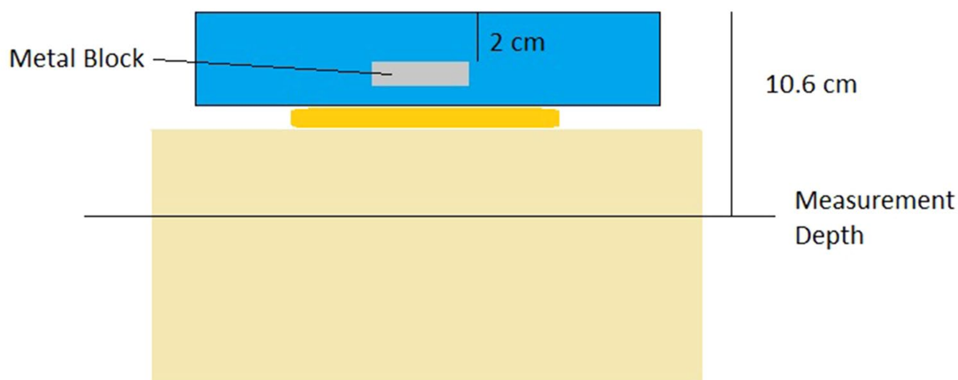

Fig. 1 Diagram of the phantom setup showing dimensions

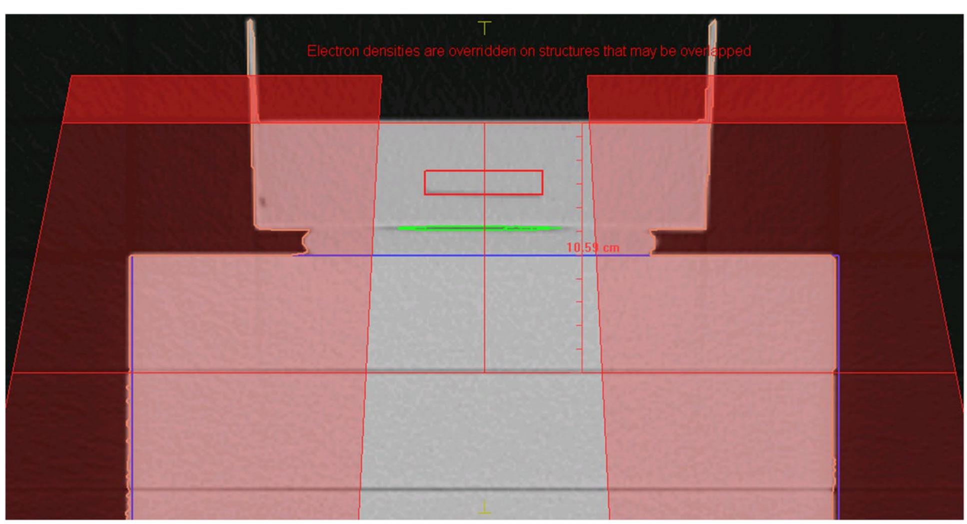

Fig. 2 Screen capture of phantom setup in Monaco after contouring

$$\% \, Difference = \frac{(D_{TPS,metal} - D_{IC,metal})}{D_{IC,metal}} - \frac{(D_{TPS,\,no\,metal} - D_{IC,\,no\,metal})}{D_{IC,\,no\,metal}} \quad (3)$$

The setup was replicated in Monaco (Version 5.11.1) with the structures contoured and overridden. A 0.3 cm grid size was used in the calculation parameters with 0.5% statistical uncertainty and dose to medium selected.

The dose plane at the measurement depth was extracted and analysed using SNC Patient 6.5 (Sun Nuclear Corp., Melbourne, FL, USA) and Microsoft excel.

Results

Point dose measurements

The difference in point dose measurements taken with the ion chamber and TPS dose are shown in Tables 2 and 3. With Table 2 showing results using actual RED and Table 3 showing results using RED calculated using Eq. 3. Table 1 also includes the difference between planned and measured values with no metal block in place. Although any setup error is considered using Eq. 3, these values indicate the performance of the methodology under relatively simple conditions before the complexity of the metal is introduced.

MapCHECK 2 measurements

The central five MapCHECK 2 diodes were used to measure the dose at the location indicated in Fig. 1. This being a 1 cm × 1 cm region of measurement. This same region was taken from TPS dose planes exported from Monaco. The difference between these doses is shown in the mean columns of Tables 4 and 5 for 6X and 15X respectively. The same correction using Eq. 3 was used.

The Max (1 cm) column in Tables 4 and 5 represents the largest percentage deviation determined for a point within the central 1 cm of the dose planes. This is included to give an indication as to the range of deviation possible for a small region beneath a metal object. Should this data be used to make clinical decisions, the largest deviation (the range) may be useful in addition to the uncertainty of the central measurement.

Discussion

This study did not attempt to address all unknowns involved in using high density metals in Monaco. As such it will not give a definitive yes or no to the question "Can I have a photon beam that goes through a metal implant" that is commonly posed by planners. This question involves weighing up many factors with differing uncertainties including: dose to structures, dose near the implant, damage to implant,

Table 2 % Dose difference between point dose measurement and TPS

Thickness of metal (cm)	Metal type							
	No metal		Al		SS		MCP96	
	6X (%)	15X (%)	6X (%)	15X (%)	6X (%)	15X (%)	6X (%)	15X (%)
0	− 1.2	− 0.7						
1			− 1.2	− 0.9	− 2.2	− 1.3	9.5	14.0
2			− 1.5	− 0.8	− 1.3	0.4	24.2	35.0
3			− 0.6	− 0.7	1.6	3.8	42.0	61.9

Performed with Al, SS and MCP96 metals with thicknesses of 1 cm, 2 cm and 3 cm. Measured at 10.6 cm depth with a Farmer chamber. Uncertainty for all point dose differences is ± 1.4%. RED for TPS calculated using Eq. 1

Table 3 % Dose difference between point dose measurement and TPS

Thickness of metal (cm)	Metal type					
	Al		SS		MCP96	
	6X (%)	15X (%)	6X (%)	15X (%)	6X (%)	15X (%)
1	− 1.5	− 1.4	− 3.5	− 2.3	2.9	7.7
2	− 2.1	− 1.6	− 3.5	− 1.2	10.7	21.9
3	− 2.2	− 1.3	− 1.2	2.2	21.3	40

Performed with Al, SS and MCP96 metals with thicknesses of 1 cm, 2 cm and 3 cm. Measured at 10.6 cm depth with a Farmer chamber. Uncertainty for all point dose differences is ± 1.4%. RED for TPS calculated using Eq. 2

Table 4 15X MapCHECK 2 differences between measured and TPS dose as calculated using Eq. 1

Metal thickness (cm)	Metal type (15X)					
	Al		SS		MCP96	
	Mean (%)	Max (1 cm) (%)	Mean (%)	Max (1 cm) (%)	Mean (%)	Max (1 cm) (%)
1	− 0.8	− 1.2	− 1.4	− 1.6	12.7	13.2
2	− 1.0	− 1.3	0.2	0.8	34.5	35.8
3	− 0.8	− 1.3	2.3	3.3	61.8	64.1

Including mean and max difference within central 1 cm. Uncertainty for all MapCHECK 2 differences is ± 1.1%

Table 5 6X MapCHECK 2 differences between measured and TPS dose as calculated using Eq. 1

Metal thickness (cm)	Metal type (6X)					
	Al		SS		MCP96	
	Mean (%)	Max (1 cm) (%)	Mean (%)	Max (1 cm) (%)	Mean (%)	Max (1 cm) (%)
1	− 0.5	− 1.2	− 2.7	− 3.2	8.2	9.3
2	− 1.3	− 1.6	− 1.7	− 2	22.9	24.6
3	− 0.9	− 1.3	0.6	1.3	40.0	42.4

Including mean and max difference within central 1 cm. Uncertainty for all MapCHECK 2 differences is ± 1.1%

geometric uncertainties and compositional uncertainties. The goal of this is to remove one such uncertainty surrounding the use of metal implants in Monaco.

The composition of an implant is usually unknown and this study does not attempt to give results for all available materials. Stainless steel and common cobalt chromium alloys are very similar in electron and physical density. This study aims to be a spot check of three metal types in order to validate the Monaco Monte Carlo algorithm. The accuracy of Monaco can potentially be assumed for similar metal types, or the methodology outlined in this study can be repeated for other common metals such as titanium or Cobalt Chromium alloys.

The difference between IC and MapCHECK 2 measured values and Monaco is shown in Tables 2, 3, 4 and 5. For IC measurements the values ranged from − 2.2 ± 1.4% to 3.8 ± 1.4% when using Eq. 1 for stainless steel and aluminium. With little variation caused by increasing thickness. In contrast, MCP96 results in, at least, a 9.5% difference between Monaco and measurements, a factor which increases with metal thickness. These factors indicate that the ability of Monaco to calculate the photon transport through different metals is diminished when metals with a density significantly higher than steel are used.

Using the RED values calculated using Eq. 3 made changes to the results which ranged from − 0.3 to − 1.6% for Al and − 1 to − 2.8% for SS. This may be considered clinically significant for some. As the physical composition of these materials is only known within a range, it is reasonable for different RED values to be used for metal types. These RED values did make a significant difference to the calculated values for MCP96. Use of this RED in the TPS makes the photon transmission far more accurate for MCP96, especially when only 1 cm was used.

For Al and SS the ability of Monaco to accurately calculate dose did not dramatically change as the metal thickness increased to 3 cm. It is unlikely for any implant to have a total linear thickness greater than 3 cm as large hip prosthetics are typically hollow.

Despite the similar relative electron density, the photon transport through MCP96 was overestimated when compared to stainless steel. This is due to the increased physical density between the two. When considering what type of interactions occur in a material when a photon beam is incident the energy and physical density play a major role. Emission of particles as a result of interaction between the high energy photon and nucleus of the atom will increase as physical density and photon energy increase. Without using information on the physical density for each structure the calculation algorithm is not able to accurately model this. There are many patients with small implants made of gold whose density far exceeds lead. It is therefore worth noting that Monaco should not be considered reliable when beams are incident on gold or other extremely high density metals. At a certain atomic number the ratio of neutrons to electrons does not increase at a constant rate. Using only electron density as a method of distinguishing materials therefore should not be used in a radiotherapy TPS beyond a certain point. Dose calculations performed by Monaco in phantoms and patients involving high density materials should therefore not be considered accurate. When performing treatment planning using materials with density similar to MCP96, a large dose uncertainty should be assumed for thicknesses greater than 1 cm and for photon energies greater than 6 MV. It should also be assumed that Monaco is overestimating the dose downstream from such high density implants and current recommendations [4] to avoid such metal implants should be followed.

The difference between Monaco calculations of dose and measured values in the presence of high Z metals is stark. According to the Monaco documentation "the error in dose deposition in lead can be as high as 5%, however even in this case the accuracy of radiation transmission is not degraded" [10]. However, the paper cited does not examine dose deposition or accuracy of radiation transmission in materials of RED greater than 3. Furthermore, Eq. 1 is stated in this paper as only being valid for natural body tissues and that for metal implants the electron density must be specified explicitly.

The 10 cm × 10 cm field size used reflects field sizes used in conformal treatments (reference for metal hips treatment). This however may not reflect realistic segment sizes in a modern VMAT treatment. The primary beam photon attenuation of the metals may therefore be underestimated in this study due to broad beam scatter. This should be considered when using small segment widths incident on an implant. In the likely event that an implant is not a 5 cm × 5 cm × 1 cm metal block and is in fact an implant shaped implant, this impact as well as different field size, depth, inaccurate contouring and other contributions to uncertainty will have to be considered separately by the planning team.

The results from this study suggest otherwise, at least for an alloy like MCP96. Previous studies found differences between measurements and Monaco of up to 23% [1] and differences using other planning software of up to 10% [2–4, 6, 7]. These however typically contained full prosthetics rather than simple shapes. Therefore, the difference in results can potentially be attributed to inaccurate geometrical assignment or electron densities within Monaco [12]. Such studies could be extended by repeating the methodology using a basic shape of similar size and composition to the implant [1–4, 6, 7]. This problem may be minimised by using modern CT scanners with artefact reduction or by using modern image registration software [5].

Conclusion

Monaco's ability to calculate dose deposited in tissue downstream of metal structures has been defined using a direct measurement method. Utilising rectangular prisms of a known material has removed most of the uncertainty due to contouring and electron density determination. These results indicate that photon transport through aluminium and stainless steel are accurately represented in Monaco while lead and bismuth alloys are not. The impact of any dose discrepancy will depend on the treatment type and planning technique utilised. For instance in Volumetric Modulated Arc Therapy a small proportion of the total dose passing through metal hips may result in an acceptably small uncertainty in the total dose to the target or OAR which may be acceptable to a Radiation Oncologist. Even if the fluence through the implant is restricted somewhat, which will drastically reduce this impact, the optimiser gains a greater degree of freedom which has the potential to lead to an optimal plan and better outcomes for the patients.

If treating through metal implants is to become mainstream the process and protocols require a multidisciplinary approach. The outcomes of this study will help to quantify the dose uncertainty at depth and will therefore remove an aspect of uncertainty during the planning process.

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Compliance with ethical standards

Conflict of interest All authors declares that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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