Publishable Summary for *16NRM03* RTNORM
k_Q factors in modern external beam radiotherapy applications to update IAEA TRS-398

Overview

Radiotherapy is a commonly used treatment for diseases, particularly cancer. The International Atomic Energy Agency IAEA TRS-398 'Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water', urgently needs updating to incorporate the latest developments in commercially available ionisation chambers, treatment modalities and the associated data. This project has been measuring $k_{Q,Q0}$ factors traceable to absorbed dose to water primary standards for a selection of ionising chambers and has been calculating $k_{Q,Q0}$ factors using modern Monte Carlo codes for medium energy x-rays, conventional (filtered) and flattening filter free (FFF) MV photons, and scanned proton beam modalities. The validated, measured, and calculated $k_{Q,Q0}$ factors that are resulting from the concerted efforts of this project are being provided to the IAEA to contribute to the revision of the IAEA TRS-398 Code of Practice.

Need

3.4 million Europeans are diagnosed with cancer every year and about half of the resulting treatments involve radiation therapy with ionising radiation. Accurate beam delivery and dosimetry are critical for successful and safe treatments. Hospital physicists are therefore required to perform measurements in accordance with validated measurement codes of practice or protocols, ensuring that doses delivered to patients at European hospitals are traceable to the quantity 'absorbed dose to water' measured in the SI unit gray (Gy). It is important that such a protocol is to be able to correct the dosimeter response for differences between the beam quality, which relates to the energy distribution of the radiation field, at the calibration laboratory (Q_0) and the beam qualities at the hospitals (Q). These corrections are called 'beam quality correction factors' and are known as $k_{Q,Q0}$.

The IAEA issued such a code of practice (the 'TRS-398') in 2000, which is the *de facto* norm for external beam radiotherapy dosimetry and is used on a worldwide basis. The data in TRS-398 include values of $k_{Q,Q0}$ factors that were calculated for clinical radiotherapy beams over the entire range of beam modalities that were available in the mid-1990s. Since the IAEA TRS-398 Code of Practice was first published, there have been significant advances in at least four areas: (i) treatment technology, including new beam modalities such as scanned proton beams and flattening filter free photon beams, (ii) detector technology, *i.e.* new ionisation chamber types, (iii) improved metrology including the availability of new primary standards, and (iv) improved Monte Carlo simulation techniques. Prior to the start of the project, a major revision of 6 chapters of the IAEA TRS-398 was initiated in 2016 with a planned completion in 2019. New measured and calculated $k_{Q,Q0}$ factors based on modern treatment modalities, equipment, and computational codes were therefore required for this update. Therefore, the IAEA issued calls for organisations, or consortia, to determine and provide up-to-date data for the TRS-398. To achieve this, $k_{Q,Q0}$ factors traceable to absorbed dose to water primary standards needed to be measured and calculated for a selection of beam modalities and ionising radiation dosimeters (ionisation chambers).

Objectives

The overall objective of this project is to provide, following a data validation procedure, both measured and calculated values of $k_{Q,Q0}$ factors for a series of ionisation chambers and for a range of radiation beam modalities, namely medium energy (kV) x-rays, conventional (filtered) and flattening filter free (FFF) MV photons, and scanned proton beams, which together will contribute to the on-going revision of three of the six chapters being updated in the IAEA TRS-398 Code of Practice.

The specific objectives of the project are:

1. ***kV x-ray beams between 100 kV and 250 kV:*** (i) to measure $k_{Q,Q0}$ factors for 3 types of ionisation chambers and 6 radiation beam qualities, ensuring direct traceability of the $k_{Q,Q0}$ factors to primary standards of absorbed dose to water; (ii) to calculate $k_{Q,Q0}$ factors for these beams using several validated Monte Carlo codes; (iii) to compare the measured and calculated $k_{Q,Q0}$ factors for kV x-ray beams, and to provide IAEA with a validated consistent new dataset of $k_{Q,Q0}$ factors with target standard uncertainties better than 1.0 %.
2. ***High-energy- (MV) photon beams between 4 MV and 20 MV, including flattening filter free beams (FFF):*** (i) to measure $k_{Q,Q0}$ factors for at least 6 types of ionisation chambers and a range of beam qualities, ensuring direct traceability of the $k_{Q,Q0}$ factors to primary standards of absorbed dose to water; (ii) to calculate $k_{Q,Q0}$ factors for these beams using several validated Monte Carlo codes; (iii) to compare the measured and calculated $k_{Q,Q0}$ factors for high-energy- (MV) photon beams, and to provide IAEA with a validated consistent new dataset of $k_{Q,Q0}$ factors with target standard uncertainties better than 0.7 %.
3. ***Scanned proton beams between 60 MeV and 250 MeV:*** (i) to measure $k_{Q,Q0}$ factors for at least 4 types of ionisation chambers and a range of beam qualities, ensuring direct traceability of the $k_{Q,Q0}$ factors to primary standards of absorbed dose to water; (ii) to calculate $k_{Q,Q0}$ factors for these beams using several validated Monte Carlo codes; (iii) to compare the measured and calculated $k_{Q,Q0}$ factors for scanned proton beams, and to provide IAEA with a validated consistent new dataset of $k_{Q,Q0}$ factors with target standard uncertainties better than 2.0 %.
4. To work closely with the IAEA task group 'Update of TRS-398', to ensure that the outputs of the project are aligned with their needs toward the revision of the Code of Practice, therefore providing experimental and calculated data that can be incorporated in the upcoming revision of the Code of Practice. To facilitate the take up of the project’s outputs by the end-users e.g. clinics, hospitals and manufacturers of ionisation chambers.

Progress beyond the state of the art

Updated $k_{Q,Q0}$ factors for kV x-rays

Prior to the start of this project, dosimetry in radiotherapy treatments using kV x-ray beams was largely based on primary standards for air kerma. In order to express dosimetry in terms of absorbed dose to water, current codes of practice include a conversion procedure based on several correction factors, which introduces additional uncertainties and leads to potential errors. While this approach remains valid, this research project supports a framework based on the direct use of the quantity of interest, absorbed dose to water. In this framework, the use of ionisation chambers relies on the application of measured and calculated $k_{Q,Q0}$ values for a selection of beam qualities at the required reference conditions. These $k_{Q,Q0}$ values will be estimated through measurements traceable to recently developed absorbed dose to water primary standards for kV x-rays, a set of *unique calorimeters*, and calculated using Monte Carlo codes.

Updated $k_{Q,Q0}$ factors for high-energy (MV) photons

Dosimetry in radiotherapy treatment using high-energy photons is already underpinned by the availability of primary standards for absorbed dose to water. However, since the publication of the current version of the TRS-398 code of practice (2000) new commercial ionisation chambers models and new radiation beam modalities (*e.g.* flattening filter-free beams) have emerged. This project is delivering new absolute dosimetry measurements and supporting Monte Carlo simulations for these new beam modalities, using a range of calorimetric standards, and new datasets of $k_{Q,Q0}$ values which are expanding beyond those currently available.

Updated $k_{Q,Q0}$ factors for scanned proton beams

Although some existing dosimetry codes of practice mention scanned proton beams, no specific guidance is yet provided. Recent modelling has shown that the measured ion recombination correction factor in a scanned proton beam is significantly different from both continuous and pulsed beams. The requirements for absorbed dose reference conditions and beam quality parameters appropriate to scanned proton beams are only just becoming clear, and new absolute dosimetry measurements are required to determine $k_{Q,Q0}$ values. This project will deliver datasets of $k_{Q,Q0}$ values measured in scanned proton beams using a graphite calorimeter and advanced methods to correct for ionisation chamber response. Moreover, several Monte Carlo codes for dosimetry with scanned proton beams will be validated so that they can be used, in the future, for dosimetric calculations in those cases where access to proton acceleration facilities is limited.

Contribution to the revision of the TRS-398 Code of Practice

Measured and calculated datasets for kV x-rays, MV photons and scanned proton beams will each be compared to provide a consistent, validated set for submission to the IAEA TRS-398 revision workgroup. To this end, the project partners are working on shared inputs: by sharing digital information such as the phase-space files that describe the radiation sources for the Monte Carlo computations, by sharing physical information, such as the x-ray radiographs of the ionisation chambers used in this project, and circulating instruments for cross-calibrations. This information-sharing strategy goes beyond both the measuring and the computational capacity of any individual partners and will provide insights in the variations that may arise between the measured and the computed values, prior to the submission of results to the IAEA task group 'Update TRS-398'.

Results

Updated $k_{Q,Q0}$ factors for kV x-rays

For kV x-rays (radiotherapy), measurements were done by CEA, ENEA and VSL in a total of 6 x-ray beam qualities for 3 ionisation chamber types. These measurements consisted of absorbed dose to water, D_w, with the available calorimeters, air-KERMA, K_a, with the available free-air-chambers. A total of 15 ionisation chambers (5 × NE2571, 5 × PTW 30013 and 5 × IBA FC 65-G) were calibrated in terms of D_w and K_a. CEA has finalized the analysis of their data, ENEA and VSL have finished the measurements and are currently working on the analyses. The same 3 types of ionisation chambers used for the measurements were modelled for Monte Carlo calculation in the same beam qualities. Here, ENEA and THM have performed Monte Carlo calculations with the EGSnrc code for all chamber types, while IST-ID performed Monte Carlo calculations for the NE2571 ionisation chamber with two different Monte Carlo codes (EGSnrc and PENELOPE). The calculations are currently being finalized and analysed. After finalization of all results, datasets of measured calibration coefficients and Monte Carlo calculations will be compared and both the conversion of ionisation chamber N_K to N_{Dw} (supporting the current formalism) and the $k_{Q,Q0}$ factors (to support the future formalism) will be validated based upon these results. Overall, this set of results is on target with respect to the progress towards Objective 1.

Updated $k_{Q,Q0}$ factors for high-energy (MV) photons

For MV x-rays (radiotherapy), $k_{Q,Q0}$ values have been calculated with the Monte Carlo code EGSnrc applying ICRU n° 90 recommendations for 9 different ionization chamber types (Exradin A1SL, IBA CC13, IBA FC65-G, IBA FC65-P, NE 2571, PTW 30013, PTW 31010, PTW 31013 and PTW 31021) in beams with and without flattening filters. For some types of ionization chamber types $k_{Q,Q0}$ values were calculated by several partners. So far, the calculations from these partners are in nice agreement with each other with a maximum deviation of 0.3 %. The volume-averaging corrections must be taken into account if the corrections are different between the water volume used to calculate the absorbed dose to water and the cavity volume of the ionization chamber used to calculate the absorbed dose to air (strong beam anisotropies or large difference between the ionization chamber cavity volume and the water volume).

New $k_{Q,Q0}$ values based on graphite calorimetry have also been measured for 3 ionization chamber types (NE 2571, Exradin A1SL and PTW 30013) in beams with flattening filters (cFF). Some ionization chamber types $k_{Q,Q0}$ have been measured by two partners. Although the measured $k_{Q,Q0}$ values produced by two different partners are also for now in good agreement with each other (maximum deviation of 0.3 %), they are systematically lower (from 0.4 % to 0.8 %) than those obtained using Monte Carlo calculations.

Three papers have been published in peer-reviewed journals (Czarnecki *et al* 2018; de Prez *et al* 2018; Pimpinella *et al* 2019). Overall, this set of results is on target with respect to the progress towards Objective 2.

Updated $k_{Q,Q0}$ factors for scanned proton beams

For scanned proton beams, KU Leuven and THM have compared the performance of different Monte Carlo codes (PENH, FLUKA and TOPAS/Geant4) to calculate $k_{Q,Q0}$ factors in scanned proton beams. For simplified geometries the three codes were found to agree within 0.7%.

Furthermore, KU Leuven has calculated $k_{Q,Q0}$ factors for 9 different plane-parallel ionization chambers and 6 Farner-type cylindrical chambers in proton beam qualities ranging from 60 to 250 MeV using the Monte Carlo code PENH. These values were provided to the IAEA in December 2018. Overall, this set of results is on target with respect to the progress towards Objective 3.

Contribution to the revision of the TRS398 Code of Practice

In compliance with the expectations of the TRS-398 Update IAEA groups, several datasets were submitted in December 2018 to the IAEA, covering all the three areas of the project (kV x-rays, MV photons, and scanned proton beams) and both origin (experimental, Monte Carlo). Overall, the submission of these data is on target with respect to the progress towards Objective 4.

Impact

This project's key route to a high impact will be the publication of its unique measured and calculated data in the revision of TRS-398. During the TRS-398 revision process, the IAEA will receive data from all over the world, and the IAEA will compile the best available information. This project ensures that the IAEA receives high-quality data for the key European detectors and for new treatment modalities directly applicable to the medical physics communities at the cancer centres in Europe.

Impact on clinical communities

The IAEA TRS-398 is the world's leading protocol for radiotherapy dosimetry and has been endorsed by organisations such as the World Health Organization (WHO) and the European Society of Therapeutic Radiology and Oncology (ESTRO). The IAEA TRS-398 is used worldwide, in Europe and beyond-. The data obtained in this project are critical for dosimetry underpinning accurate cancer treatments in Europe. The $k_{Q,Q0}$ factors are essential for current and future dosimetry with ionisation chambers in modern clinical beams. This project will therefore have a direct and substantial impact since European radiotherapy clinics use this code of practice on a daily basis for critical tasks, such as the calibration of linear accelerators used in external-beam radiotherapy. This project will ultimately affect the 1.7 million citizens undergoing radiotherapy cancer treatment annually as radiotherapy clinics will use and rely on the correction factors and measurement procedures described in the planned revision of the TRS-398.

For reference dosimetry, hospitals generally will not use correction factors directly from the scientific literature, and hence in order to comply with TRS-398 the correction factors for their type of reference dosimetry ionisation chamber need to be included in that norm. In the case where new treatments are available for which the reference dosimetry is not covered in TRS-398 (such as flattening filter free photon beams), hospitals may have to resort to alternative procedures or they may decide not to offer the treatments to patients. The outputs of this project will therefore lead to further harmonisation of clinical reference dosimetry for both conventional radiotherapy modalities and recently developed beam modalities and enable hospitals and clinics to improve their existing radiotherapy and to adopt new treatment modalities.

Knowledge transfer to stakeholders such as medical physicists will primarily be achieved through participation in national and international conferences, peer-reviewed publications, workshops, and both education and training. The results from this project will be integrated into existing training services provided by the partners (e.g. courses in reference dosimetry, regulatory work).

Impact on industrial and other user communities

This project ensures that data for the leading producers of ionisation chambers (including European industry) and manufacturers of treatment equipment will be available for the IAEA TRS-398. This will enhance their economic position, since ionisation chamber models that are not in the TRS-398 will not be used for reference dosimetry at hospitals. European manufacturers of radiotherapy facilities have recently developed innovative new radiotherapy modalities such as scanned proton beams and flattening filter free (FFF) photon beams. They will benefit from the updated data sets determined in this project, as it will provide data which is lacking in the current IAEA TRS-398 and which will ensure that these new modalities can be safely adopted in radiotherapy clinics.

Impact on the metrology and scientific communities

One of the absorbed dose to water standards has been used on two of the major commercially available clinical accelerators (De Prez et. al 2018). This strengthens confidence in the use of the beam quality specifier for these radiation therapy modalities. Additionally, this project has shown what impact the adoption of the ICRU report no. 90 recommendations is having on calculated correction factors for reference dosimetry (Czarnecki et. al 2018, Pimpinella et. al. 2019).

Impact on relevant standards

This project focuses on the update of data that will be central for the revision of the IAEA TRS-398, the world's leading dosimetry Code of Practice. In so doing, this project embraces the fundamental ideas underpinning the Code of Practice, which is to organise radiation dosimetry in a coherent manner and provide traceability to primary standards of absorbed dose to water.

Longer-term economic, social and environmental impacts

In line with what inspired the first edition of the TRS-398 Code of Practice, the coherence that is ensured by the concerted traceability to primary standards of absorbed dose to water, in all radiation therapy modalities, will result in the simplification of clinical dosimetry procedures, will reduced the risk of errors, and will overall strengthen the confidence in cancer radiotherapy. An improved radiotherapy will offer both social and economic benefits in the form of better treatments, better therapeutic outcomes and patient survival.

List of publications

Pimpinella M, Silvi L and Pinto M 2019 Calculation of k_Q factors for Farmer-type ionization chambers following the recent recommendations on new key dosimetry data *Physica Medica* **57** 221–30

de Prez L A, de Pooter J A, Jansen B, Perik T and Wittkämper F 2018 Comparison of k_Q factors measured with a water calorimeter in flattening filter free (FFF) and conventional flattening filter (cFF) photon beams *Physics in Medicine and Biology* **63** 45023

Czarnecki D, Poppe B and Zink K 2018 Impact of new ICRU Report 90 recommendations on calculated correction factors for reference dosimetry *Physics in Medicine and Biology*l **63** 155015

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