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 will measure $k_{Q,Q0}$ factors traceable to absorbed dose to water primary standards for a selection of ionising chambers and will also calculate $k_{Q,Q0}$ 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 will be provided to 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 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 (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. A major revision of 6 chapters of 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 are therefore required for the update. The IAEA has 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 need 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 validated measured and calculated values of $k_{Q,Q0}$ factors for a series of ionisation chambers and 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 will contribute to the on-going revision of three chapters of the Code of Practice IAEA TRS-398.

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 at least 4 types of ionisation chambers and at least 8 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 8 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 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

Dosimetry in radiotherapy treatments using kV x-ray beams is currently 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 errors. This project will support a framework for the use of ionisation chambers based on measured and calculated $k_{Q,Q0}$ values for a selection of beam qualities and a range of ionisation chambers at the required reference conditions. These $k_{Q,Q0}$ values will be 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 new ionisation chambers and new radiation beam modalities (*e.g.* flattening filter-free beams) have emerged. This project will deliver 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 will expand 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 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. The partners will work on shared inputs: specifically sharing digital information, such as the phase-space files that describe the radiation sources for the Monte Carlo computations, and physical information, such as the x-ray radiographs of the ionisation chambers used in this project. This information sharing strategy goes beyond both the measuring and the computational capacity of 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

In liaison with the IAEA TRS 398 revision Core Group, a consensus was reached over the conditions and beam qualities that underpin both the (current) air kerma-based and the (tentative) absorbed dose to water-based approach in the definition of the k_Q factors, and a k_Q data comparison protocol drafted. Measurements of absorbed dose to water in the x-ray qualities agreed in the measurement protocol have been performed using the primary standards, in some cases after adapting them to the agreed beam qualities. Calibration of ionization chambers in terms of the quantities absorbed dose to water and air kerma is planned for the second period of the project. Information on the ionisation chambers' geometries has been obtained from manufacturers and modelling of the NE 2571 chamber completed.

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

A set of beam qualities for which the $k_{Q,Q0}$ values will be determined (for clinical use and comparison purposes within the project) has been agreed with IAEA. Significant experimental and modelling work has been carried out for high energy photon beams. A key result is the application of the Dutch primary standard for absorbed dose to water measurements in flattening-filter free (FFF) MV photon beams. This work is the first of its kind that directly compares k_Q factors measured with the same primary standard in both FFF and conventional photon beams. A number of ionization chambers have been characterised including some of the main ones in use at European hospitals (IBA FC65G, PTW 30013 and NE2571). Preliminary experimental results indicate that the models for at least some of the characterised chambers have a highly uniform response in MV photon beams, which supports the approach of using generic k_Q factors. Complex geometrical models of the ionization chambers have been developed based on detailed information from industry as well as extensive validation tests based on the Fano theorem. An important outcome from the modelling work is a study of the role of the newly published ICRU 90 report on the computation of k_Q factors and beam quality specifiers. Two papers were published in peer-reviewed journals.

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

Beam qualities for scanned proton beams and reference conditions for plane-parallel type ionisation chambers have been defined. Reference conditions for thimble type chambers have yet to be defined. Discussions are ongoing with the IAEA task group regarding the reference conditions for scanned proton beams for cylindrical chambers, and measurements will not start until these are fully defined by IAEA. PENELOPE, EGSnrc, Geant4 and FLUKA Monte Carlo codes were benchmarked against one another. Using these codes Monte Carlo calculations of the absorbed dose to medium in both water and air cavities were performed under 'IAEA TRS-398 Update' reference conditions for Cobalt-60 and scanned proton beams and chamber-specific f_Q-factors and k_Q-factors derived from these quantities. The f_Q- and k_Q-factors for these simplified geometries agree with each other within 1 % or better. A paper is in preparation.

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

The consortium has liaised by email with the Task Group leader responsible for the 'IAEA TRS-398 Update', in particular regarding achieving a consensus on the reference conditions and beam qualities for the 3 types of radiation beam modalities.

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, including in most European countries. 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 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 metrological and scientific communities

One of the absorbed dose to water standards has been used on two of the major commercially available clinical accelerators. 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).

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.

Impact activities

The rtnorm.eu website provides basic information about the project, including links to partners and the publishable summary. The project has been highlighted at various national meetings with end users such as hospital physicists in Italy, Germany, Spain and Japan, and scientific presentations at international conferences e.g. MCMA2017 and ESTRO 37 (the European Society of Therapeutic Radiology and Oncology). Work has also been prepared for presentation, for example, at the upcoming European Congress of Medical Physics in Copenhagen in August 2018. The main scientific journal publication at this point of the project is the Dutch study of FFF versus cFF results. The modelling results related to the rule of the ICRU 90 report is expected to be the next important publication outcome.

List of publications

L. de Prez, J. de Pooter, B. Jansen, T. Perik and F. Wittkämper: 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**(4), 2018, doi.org/10.1088/1361-6560/aaaa93.

D. Czarnecki, B. Poppe and K. Zink: Impact of new ICRU Report 90 recommendations on calculated correction factors for reference dosimetry, Physics in Medicine and Biology, **63**(15), 2018, doi.org/10.1088/1361-6560/aad148.

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 May 2017, 24 months</td></tr>
<tr><td colspan="3">Coordinator: Massimo Pinto,
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<tr><td>Internal Funded Partners:
1 ENEA, Italy
2 CEA, France
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