Final Publishable JRP Summary for HLT09 MetrExtRT
Metrology for radiotherapy using complex radiation fields

Overview

Advances in technology have enabled the introduction of new, complex forms of radiotherapy for the treatment of cancer, including different energies, particles, beam widths and scanning techniques. The doses and delivery methods are often far removed from established reference dosimetry conditions and standards. While the tissue being targeted for treatment may be well defined to reduce damage to surrounding healthy tissue, the accuracy with which the dose is delivered may fall short of the requirements given by ICRU (International Commission on Radiation units and Measurements). The project developed primary standards and good practice guidelines to improve the accuracy of dose measurements made in a clinical setting, enabling clinicians to demonstrate that the delivered dose matches the planned treatment.

Need for the project

Modern radiotherapy treatments aim to deliver the appropriate dose to the tumor to kill the cancer cells while saving the surrounding healthy tissue. This is achieved using complex radiation fields that deliver intense radioactive doses to areas of only a few millimeters across, or via brachytherapy where the radiation source in placed inside the body as close as possible to the tumour. Too low a dose in the target volume increases the risk of treatment failure through recurrence of the cancer, while too high a dose can result in higher incidence of severe side effects.

Today, in modern photon radiotherapy dose accuracies of about 8 % can be achieved, but in high-energy photon, electron and particle therapy the accuracy is much lower. The project aimed to address the urgent need for further advancements in dosimetry in radiotherapy and improve methods to bridge the gap between the high-level reference standards and clinical conditions. This current lack of traceability to established reference dosimetry and primary standards makes it more difficult to meet the requirement of ICRU Report 24.

The absorbed dose to water is the basic quantity in dosimetry for radiation therapy. Whilst absorbed dose to water based protocols are widely used for reference dosimetry for high energy photons, this is not the case for other radiotherapy modalities such as low and medium energy x-rays. Particle beam dosimetry is based on calibrations in high-energy photon beams and using correction factors for the difference in beam quality, this combination has a considerable uncertainty. Direct calibrations in terms of absorbed dose to water are not available for scanned ion beams but, in principle, can be derived for other radiation types and the associated correction factors.

In order to improve the situation, it is necessary to develop all steps of the metrological chain from the primary standards through to verification of the dose in and around the tumour. Specifically this necessitates developing new primary standards of absorbed dose to water; studying new detectors and improving knowledge of the characteristics of existing detectors useable for quality control and in vivo dosimetry; and publishing guide lines of good practice on their use.

The project looks at complex forms of radiation where there is no traceability to existing references or no references and high uncertainties. This may refer to different particles, different energies, the size of the beam, the number of beams and or the different angles.

EMRP
European Metrology Research Programme
Programme of EURAMET

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Scientific and technical objectives

The project has five distinct objectives to develop new primary standards where a lack of reference standards complying with the international protocol has been identified. These new standards will be based on calorimetric and ion chamber techniques, which will require considerable technological developments.

The scientific and technical objectives for the project are:

1. To develop and compare new references in terms of absorbed dose to water for medium x-ray energies. (Before the project there was no direct traceability through the absorbed dose to water measurement.)
2. To study new integral quantities for the characterisation of high energy x-rays for SRS and SRT (stereotactic radiosurgery and radiotherapy) and IMRT (imaging modulated radiotherapy). (The treatment conditions are too far from the reference ones involving rotating beams, and correction factors would lead to high uncertainties).
3. To improve the consistency and traceability of proton and carbon ion beams, in particular novel types such as scanned particle beams. (These heavy charged particles can reach the tumour with smaller dose to the surrounding healthy tissue, but because the beams are narrow they are used in a scanning mode. There are no references for this type of irradiation)
4. To develop a traceable measurement system for the verification of dose and distribution in complex radiation fields for the verification of treatment planning systems (TPS). (This objective looked at high energy radiation)
5. To develop a metrological chain, from the primary standard to the end user's calibration and treatment verification, for the use of low energy x-rays for brachytherapy. (Brachytherapy involves the low energy x-ray tubes being inside the body, and hence closer to a tumour, and again there are no standards for this situation.)

Results

To develop and compare new references in terms of absorbed dose to water for medium x-ray energies.

The project developed and validated new reference standards for 'absorbed dose to water' for medium x-ray energies with water/graphite calorimeters. This is important in the delivery of radiotherapy. It looked at the calibration methods in different laboratories and clinical situations, to ensure consistency. The objective was achieved in full, and the results have led to new services for the end users.

To study new integral quantities for the characterisation of high energy x-rays for SRS and SRT (stereotactic radiosurgery and radiotherapy) and IMRT (imaging modulated radiotherapy).

The project studied the characterisation of high energy x-rays used for therapy. In high energy photon radiotherapy, the size of the irradiation beams for routine treatments is approximately one cm^2, meaning that it is not covered by current protocols. To overcome this difficulty LNHB built a calorimeter with a sensitive area larger than the radiation field dimensions, so that it was used to measure the energy deposited by the whole radiation beam though a concept similar to the dose area product (DAP) well known in radio diagnostics. The use of such a concept is a breakthrough compared to the former concept of dose at a single point on which the current traceability protocol are based.

To validate the use of DAP, a comparison with the conventional calorimeters used to measure point dose quantity down to 2x2 cm^2 beam was made. It shows that the two methods are compatible within one standard uncertainty. Transfer standards based on in-house and commercially available ionisation chambers and new quality index based on DAP ratio between 20 cm and 10 cm were checked successfully. This objective proved that absorption dose to water on the surface can be used to establish the dose to water references and transfer them to the end users. It is still needed to check the behaviour of this new reference in clinical situations where the radiation field is delimited by a multi-leaves collimator. As the DAP quantity is not implemented in treatment planning system, provided by the LINAC manufacturer, promising results have been found to convert the DAP into evaluated point absorbed dose using 2D film dosimeters.

Another possibility to overcome the lack of primary standards for very small radiation fields is the use of point like detectors associated with suitable correction factor based on the spatial response of the transfer dosemeters was studied at PTB. The spatial response and internal structure of commercially available ionisation chambers of different sizes (650 mm^3 to 16 mm^3) and shape (cylindrical and plane parallel) and diodes was studied in high energy photon and electron beams but it turns that the correction is too complex for regular clinical use at this stage.

To improve the consistency and traceability of proton and carbon ion beams, in particular novel types such as scanned particle beams.

For hadron therapy, a new smaller water calorimeter was built for absorbed dose measurements in a 190 MeV proton beam and a 430 MeV/u carbon ion beam. Correction factors for both water and graphite calorimeters were determined and validated in scanned beams to derive absorbed dose to water, to study the correction factors to be applied to ionisation chamber measurements in scanned beams experimentally and by means of calculations, to study the water equivalence of alanine and radiochromic films and other water equivalent phantom materials in high energy protons beams has been experimentally determined. The objective established the correction coefficients to convert the measurements for a scanned beam.

To overcome the current lack of metrological chain for low energy x-rays in terms of absorbed dose to water used in electronic brachytherapy

Radiation fields produced by INTRABEAM and AXXENT have been characterised by means of improved spectrometry techniques and Monte Carlo calculation. Both measurements and simulations were in good agreement. The 3D dose distribution in water with and without applicators was investigated using X-ray storage foils and a plastic scintillator device developed at PTB. A primary standard in term of absorbed dose to water based on an extrapolation chamber have been optimized through a better knowledge of the interaction coefficient for phantom material. Dose measurements were performed with standard uncertainty less than 3%.

To develop a traceable measurement system for the verification of dose and distribution in complex radiation fields for the verification of treatment planning systems (TPS).

Former attempts to use synthetic or natural based diamond detector as secondary standard failed because of the lack of reproducibility. The PTW firm made new dosemeter, based on synthetic diamond detectors developed by ENEA and Tor Vergata Rome University within the framework of this research project, commercially available as a transfer dosemeter for photons and electrons in radiotherapy. A specially design new configuration of this detector for real time in vivo dosimetry allowing verifications during the treatment and therefore avoiding errors has been optimised, $K_{Q,Q0}$ values were measured for electron energies in the range 6 and 15 MeV.

In addition to the work on point passive detectors such as Alanine, the goal of the research program was to characterise 2D and 3D detectors to be used for verification of complex dose distributions in photon and electron beams. Thus, the reading protocol for EBT3 gafchromic film has been optimised and the first results of STUK show that 1% accuracy in relative dose can be achieved.

Electronic Portal Imaging Devices (EPID) are between 2D and 3D techniques because the measurement itself gives 2D information but multiple angle acquisitions and mathematical reconstruction allow the building of 3D models of the dose distributions inside the patient. As the measurement is made during the treatment the results is a “true” dose distribution which can be used to validate the TPS calculations. NPL did the first step toward this goal that is to say to study the characteristic of the detector EPID characteristics in terms of angular and energy responses have been measured and validated against Monte Carlo calculation, with some dependency on the (imprecisely known) detector material composition.

Gel dosimeters are very promising because a single measurement leads to a 3D distribution of doses allowing a direct comparison with treatment planning systems (TPS) calculations. LNHB and University d'Auverge in collaboration with University Paul Sabatier worked on this kind of detector. The composition and the manufacturing protocol of a special Fricke gel were studied, and optimised to insure the required sensitivity, reproducibility and stability over 5 hours after irradiation. This delay allows carrying the irradiated sample in front of the MRI reading facility. A software for the automatic analysis of the MRI image used to calculate 3D dose distribution from the raw reading has been made to establish a remote calculation service. All the steps for launching a new 3D dosimetry service by Université d'Auvergne are ready. Test for depth dose and profile measurement showed a good agreement with point detectors. The objective showed that a distribution of dose through a volume can be found. This means that measurements can be made in hospitals using phantoms to check the doses at the organ at risk are within the dose threshold.

The best quality control is an end to end check therefore detectors are aimed at being used anthropomorphic or semi anthropomorphic phantoms. Such a phantoms have been studied within the frame work of the project such as those which can be used to breast cancer.

Actual and potential impact

Dissemination of results

The project outputs have been shared widely with the metrology, instrumentation and clinical communities. 18 papers were published or presented at conferences.

Early Impact

The project developed methodologies, primary standards and guidance for new complex radiation treatments. The following achievements show how the results from the project are being used in research projects and in instrument development:

- The diamond detector developed by ENEA and Tor Vergata University within the framework of this contract is now included in a PTW commercially available dosimeter. This detector allows a better evaluation of output factors when commissioning the medical LINAC, so subsequently a better accuracy of the dose distribution of the treatment calculated by the treatment planning system.
- Reference standards in terms of DAP have been established to overcome the lack of direct traceability for small fields in high energy photons beams.
- Calibration with traceability to primary reference is now established for low energy x-rays in brachytherapy.
- The 3D gel dosimetry is ready to be used by end users for checking the organ at risk doses through a comparison with the TPS calculations.
- Correction factor for scanned hadron beams have been established to make available absorbed dose to water references
- Metrological use of 2D Gafchromic film has been improved to reach 1% uncertainty opening the way to use them for in vivo dosimetry.

Potential impact

The results of the project will have significant effect of future technology for radiation treatment. The work has contributed to the research on radiation metrology, and reflects the continuous evolution of the modalities and complexities of treatments. Examples include:

- The feasibility of the DAP concept for primary standard as a replacement of the dose absorbed at a point for the small fields is proven, but further improvements are needed in terms of transfer dosimetry to reach an industrial stage.

- The new chain of traceability was established for the brachytherapy electronic units, which represents an essential advancement for the safety of treatments using this modality. Prior to this work, only an indirect traceability could be achieved.
- This diamond detection technology is well suited for in vivo dosimetry to replace silicon detectors which are not tissue equivalent.
- It is not possible to do a calibration in the same conditions as those of the treatment, therefore checking the treatment plans in conditions as similar as possible to the reality is also a remarkable result allowing testing of the plans of treatment, and detection of possible errors before they have consequences. So the phantom design and built within this work and the pilot study shows reassuring results. Based on gel dosimetry studied in this work a 3D dosimetry service could be proposed to end users in the future.
- The working group for updating the IAEA 398 protocol will take advantage of the results of the project.
- The use of EPID for in vivo dosimetry was checked and the dose characteristic if the EPID were studied showing that extra work are necessary since the geometrical and material characteristics must be know with more accuracy.
- The new anthropomorphic or semi anthropomorphic phantom are potential candidates for routine use, with further improvements.

List of publications
Refer to the publications list in the Final Publishable JRP Report.

JRP start date and duration:	1 June 2012, 36 months
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JRP-Partner 3 ENEA, Italy	JRP-Partner 8 STUK, Finland
JRP-Partner 4 MKEH Hungary	JRP-Partner 9 VSL, Netherlands
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