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Dosimetry in Norwegian radiotherapy

Implementation of the absorbed dose to water standard and code of practice in radiotherapy in Norway

Statens strålevern

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Key words:
Dosimetry. Calibration protocol. Radiotherapy. Comparison.

Abstract:
Absorbed dose to water as the quantity for the calibration standard and code of practice in radiotherapy are implemented in Norway. The comparison of the ^{60}Co secondary standards showed agreement within 0.4%. The new standard and dosimetry protocol lead to 1 % lower dose to the target volume. The present dose overestimation of 1 % will not be clinically detectable.

Referanse:
Bjerke Hans. Dosimetri i norsk stråleterapi. Innføring av dosimetrinormal og dosimetriprotokoll absorbert dose til vann i Norge. StrålevernRapport 2003:11. Østerås: Statens strålevern, 2003. Språk: engelsk.

Emneord:
Dosimetri. Kalibrerings protokoll. Stråleterapi. Sammenligning.

Resymé:
Absorbert dose til vann som dosimetri normal og dosimetriprotokoll i stråleterapi er innført i Norge. Sammenligning av ^{60}Co sekundær normal med andre land viser avvik innenfor 0,4 %. Ny dosimetriprotokoll gir ca 1 % lavere dose til målvolumet. Den rapporterte overestimering av dose vil ikke kunne sees klinisk.

Head of project: Hans Bjerke.
Approved:

Gunnar Saxebøl, director, Department for Radiation Protection and Nuclear Safety.

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Edited by Hans Bjerke

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Østerås, 2003

Foreword

The Norwegian government is funding a quality assurance program to assist the clinics in both medical and physical aspects of radiotherapy as a result of a national cancer plan. This activity is led by the Norwegian Radiation Protection Authority (NRPA), and a task group for this, KVIST (KValitetssikring I STråleterapi. Abbreviation for Norwegian wording: Quality Assurance in Radiation Therapy), was established in 2000. In conjunction with this group there exists a reference group with participants from all radiotherapy centres and all relevant personnel groups (oncologists, medical physicists, radiation technologists). Much of the work is done by appointed work groups consisting of professionals from the hospitals and representatives from the KVIST group. The solutions are based on consensus to ease the implementation in the clinics, and in this way contribute and improve quality.

The implementation of an absorbed dose to water standard and a code of practice for clinical dosimetry was done by the Norwegian Secondary Standard Dosimetry Laboratory (SSDL) at NRPA.

This report is worked out in the framework of the KVIST. The dosimetry work group to implement TRS 398 for external beam radiotherapy was given a mandate to:

- *Assist the KVIST group in the implementation of TRS 398 in radiation therapy*
- *Act for a dosimetry in Norway based on TRS 398*
- *Propose actions for the implementation and use of TRS 398 at the clinics*
- *Collect and prepare dose data from the implementation of TRS 398*
- *Perform dosimetry studies in the radiation therapy beams*

This report has contributions from physicists working at the Norwegian radiation therapy centres and Nordic colleagues with special interests in radiation dosimetry. Their names are:

National dosimetry group: Elin Agathe Hult (Norwegian Radiation Protection Authority), Ida Korneliussen and Ståle Ølberg (Ullevål University Hospital), Harald Valen (Haukeland University Hospital), Per Hanisch (Sørlandet Hospital, VAS), Kjell Tverå and Jan F. Evensen (The Norwegian Radium Hospital), Oddvar Spanne (University Hospital of North Norway), Anne Strand Alfredsen (Ålesund Hospital), Anne Beate Langeland Marthinsen and Nina Levin (St. Olavs Hospital), Johan Vikström (The Rogaland Central Hospital) and Bengt Erik Johannsson (Sykehus Innlandet Gjøvik).

Nordic co-operation: Antti Kosunen and Ritva Parkkinen (Radiation and Nuclear Safety Authority (STUK)), Jan Erik Grindborg (Swedish Radiation Protection Authority (SSI)), Mathias Westermark (Karolinska University Hospital (KS)), Klaus Ennow (Statens Institutt for Strålehygiejne (SIS)) and Kjell Olsen (Herlev University Hospital).

The report enlightens Norwegian dosimetry history and dosimetry definitions. The implementation chapter contains a lot of local dosimetry experience valuable for day to day dosimetry at the clinic. Dosimetric and medical conclusions are given.

Status of the document: This document is published in the series StrålevernRapport issued by the Norwegian Radiation Protection Authority. It represents a professional national consensus and NRPA uses it as advisory in its authority lines.

Content

1 Introduction

1.1 The decision to introduce absorbed dose to water standard and its code of practice

A Nordic meeting recommended in 2001 [1] calibrations and protocols for radiotherapy using dosimetry based on absorbed dose to water standards. IAEA Technical reports series no. 398 (TRS 398) [2] was chosen as the dosimetry protocol. The Norwegian secondary standard dosimetry laboratory (SSDL) of the Norwegian Radiation Protection Authority (NRPA) performed the implementation of the new dosimetry protocol, and a national dosimetry group of medical physicists from hospitals monitored the work. A secondary standard for absorbed dose to water has been calibrated since 1991 at the Bureau International des Poids et Mesures (BIPM) in a ^{60}Co gamma beam, and calibration in water has been available.

Figure 1 Nordic meeting at NRPA January 2001.

1.2 The Norwegian system for implementing TRS 398

The system for the implementation of dosimetry based on absorbed dose to water standards, calibrations and protocols for external beam therapy consisted of:

(a) A national dosimetry group to implement and follow up the TRS 398 [2].

(b) A NRPA calibration of its own and hospital reference chambers both in air kerma and absorbed dose to water.

(c) Nationwide visits for teaching, training, cross-calibrating in electron beams and the determination of dose according to IAEA Technical Reports Series No. 277 (TRS 277) [3], IAEA Technical Reports Series No. 381 (TRS 381) [4] and TRS 398 [2].

(d) National records being set up for all photon and electron radiotherapy beams containing the dose determined by the previous and new code of practice reported by medical physicists at the hospitals. This will provide historical evidence for the shift between the two dosimetry protocols.

(e) Visits to SSDLs in Finland (the Radiation and Nuclear Safety Authority (STUK)), in Sweden (Swedish Radiation Protection Authority (SSI)) and in Denmark (Statens institutt for strålehygiejne (SIS)) and to the Laboratoire National Henri Becquerel (LNHB) in France to verify the NRPA calibration, measurements and dose determinations.

The system and progress of implementation was reviewed in IAEA co-ordinated research project No. 11627.

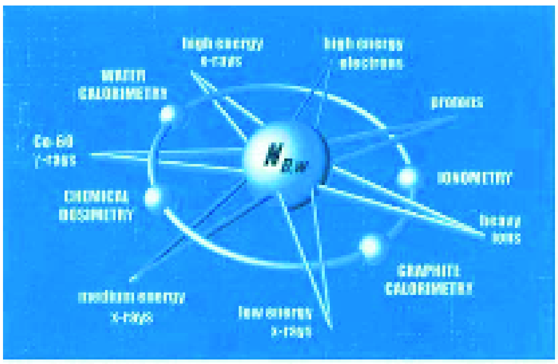


Figure 2 The system of calibration coefficient $N_{D,W}$ *established for all external radiation beam types and qualities, defined in a system of primary standards.*

2 Historical review of dosimetry units and Norwegian standards

Dosimetry in radiotherapy was established at the second meeting of the International Commission on Radiation Units (ICRU) in 1928 by saying that: "This international unit be the quantity of x-radiation". In 1937 the unit was named the roentgen with the symbol r, and in 1962 ICRU changed it to R. This historical information is given by Greening [5].

2.1 The roentgen (R)

A "substandard" for dosimetry in Norway was bought in 1933. See Figure 3.

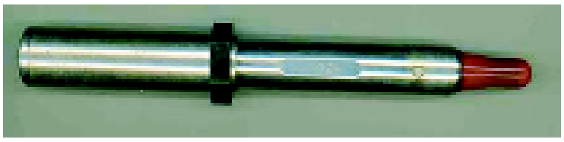


Figure 3 Vicoreen 100r chamber.

In the 1950s and 1960s, primary free air standards for low and medium energy x-rays were developed and used in the country for the determination of exposure. At this time the dosimetry laboratory was operating primary standards. See Figure 4.

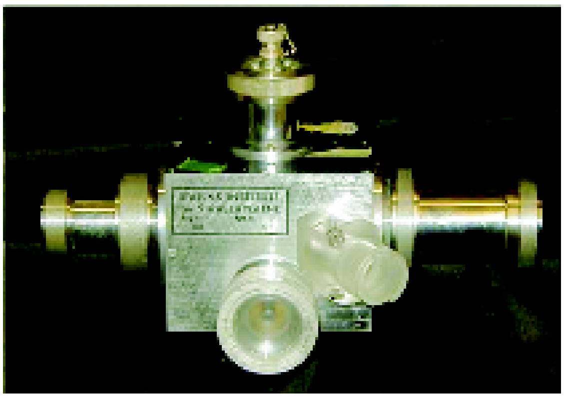


Figure 4 Free air chamber for low energy x-rays. Primary standard in Norway from 1960 to 1980.

Since 1977, a National Physical Laboratory (NPL) secondary standard instrument was established as the Norwegian standard. It was calibrated at NPL in x-ray beams up to 2000 kV in units of "roentgen".

Figure 5 NPL Secondary Standard consists of chamber, electrometer and check source.

2.2 The air kerma

The first calibration of Norwegian standards at the Bureau International des Poids et Mesures (BIPM) in a ^{60}Co gamma beam took place in November 1982. The measurements were done free in air for the determination of air kerma. The hospital reference chambers were calibrated in April 1983 in the ^{60}Co gamma beam established at NRPA. The unit was air kerma and the calibration coefficients $N_{d,a}$ were determined according to the Nordic Association of Clinical Physics (NACP) recommendations [6].

2.3 The absorbed dose to water

In 1991, the Norwegian secondary standard was calibrated in absorbed dose to water in a water phantom at BIPM [7]. The calibration of the standard was followed by a set up at the NRPA for calibration in water [8].

3 Absorbed dose to water standard and code of practice for photons and electrons

The International Commission on Radiation Units and Measurements (ICRU) have defined the quantity absorbed dose to water for high-energy photons and electrons. The definitions in paragraphs 3.1.1, 3.1.2 and 3.2.1 are taken from ICRU [9, 10].

3.1 Photons

3.1.1 Photon dose

The energy deposition by photons is a result of photon and electron interaction in water.

The mass energy-absorption coefficients play a key role in photon dosimetry. Under the assumption that secondary charged–particle equilibrium exists, the absorbed dose to water, $\boldsymbol{D_W}$, in Gy, for a given spectral photon fluence, $\boldsymbol{\Phi_E}$, is given by

$$D_w = \int \Phi_E (\mu_{en}/\rho)_w E dE \qquad (1)$$

where $\boldsymbol{\Phi_E}$, is in J^{-1} m^{-2}, the mass energy-absorption coefficient for water, $(\mu_{en}/\rho)_w$, is in m^2 kg^{-1} and the energy, $\boldsymbol{E}$ in is J. The Gy is in basic units J/kg or m^2s^{-2}.

3.1.2 Ionisation measurements in a water phantom

The conversion of the ionisation measured in the cavity of a thick-walled graphite chamber to absorbed dose to water, $\boldsymbol{D_W}$, for ^{60}Co gamma radiation in a water phantom is

$$D_w = \left(\frac{q}{m}\right)\left(\frac{W}{e}\right) s_{gr,air} k_p \qquad (2)$$

where $\boldsymbol{q}$ is the charge created in the mass $\boldsymbol{m}$ of the air in the cavity, $\boldsymbol{W}$ is the mean energy required to produce an ion pair in air and $\boldsymbol{e}$ is the elementary charge. The ratio W/e is determined by BIPM [11] and is (33.97 ± 0.05) J C^{-1} for dry air. $\boldsymbol{s_{gr,air}}$ is the ratio of the stopping powers of graphite and air averaged over the secondary electron spectrum produced by ^{60}Co, and the global perturbation factor, $\boldsymbol{k_p}$, is given by

$$k_p = k_{cav} (\mu_{en}/\rho)_{w,gr} \Psi_{w,gr} \beta_{w,gr} \qquad (3)$$

where $\boldsymbol{k_{cav}}$ is the factor correcting for in-scattering of electrons that makes the electron fluence inside a cavity different from that in the medium in the absence of the cavity. $(\mu_{en}/\rho)_{w,gr}$ is the ratio of the mass energy-absorption coefficients averaged over the photon spectrum, $\boldsymbol{\Psi_{w,gr}}$ is the corresponding ratio of the photon energy fluences at the point of interest and $\beta_{w,gr}$ is the quotient of the ratios of absorbed dose to collision kerma. This method is used in the realisation of absorbed dose to water at BIPM.

3.1.3 Calibration in ^{60}Co gamma beam at NRPA

The NRPA calibrates the hospital reference chambers in a ^{60}Co gamma beam [8]. See Figure 6. The chambers are sent every second year from the hospitals to the NRPA. These calibrated chambers serve as a link between absorbed dose to water standard at BIPM and the clinical dosimetry.

Figure 6 Calibration at the Secondary Standard Dosimetry Laboratory (SSDL) of the NRPA.

The absorbed dose to water calibration at NRPA follows the conditions for ^{60}Co calibrations given in TRS 398 [2]. The determination of dose rate is achieved using a secondary standard ionisation chamber placed at the reference point in the water phantom. The chambers from the hospitals are placed in the same reference point in the water phantom.

Calibration based on decay of determined dose rate was employed as the calibration method the first years. Since 2002 the substitution method is performed: dose determined with the standard and then substituting it with the reference chamber.

The absorbed dose to water calibration coefficient, $\boldsymbol{N_{D,W}}$ in Gy/C is determined from

$$N_{D,W} = \dot{D} / M_C \tag{4}$$

where $\dot{D}$ is the dose rate in Gy/s in the reference point determined by the secondary standard and $\boldsymbol{M_C}$ is the corrected measured current (A) from the ionisation chamber being calibrated.

The chamber may have a directional dependence and a mark on the chamber must be placed towards the source. The directional dependence may account for a deviation of up to 2 %.

The electrometer in clinical use will also need calibration. Locally, the dosimetric system is monitored and made reliable by routine stability checks of the ionisation chamber, electrometer, check source, barometer and thermometer.

3.2 Electrons

3.2.1 Electron dose

Electrons deposit energy and thus generate absorbed dose in water.

The absorbed dose to water is given by

$$D_W = \int \Phi_E (S_{col} / \rho)_W \, dE \tag{5}$$

where $\boldsymbol{\Phi_E}$ is the spectral fluence of primary electrons, and $\boldsymbol{(S_{col}/\rho)_w}$ is the unrestricted collision stopping power for water.

3.2.2 Cross calibration in electron beams

The Bjerke phantom [12] has been developed at the NRPA for cross calibration in high energy electron beams. See Figure 7. Calibration coefficients $\boldsymbol{N_{D,W}}$ for plane parallel chambers are determined at the highest electron beam quality. The dose, $\boldsymbol{D_{Qcross}}$, for 200 MUs is determined in a beam of radiation quality, $\boldsymbol{Q_{cross}}$ ($\boldsymbol{R_{50}}$ > 0.7 g/cm^2) with a cylindrical waterproof chamber. In cross calibration two reference diodes are used as monitors at a depth of 50 mm in water at the corner of the radiation field.

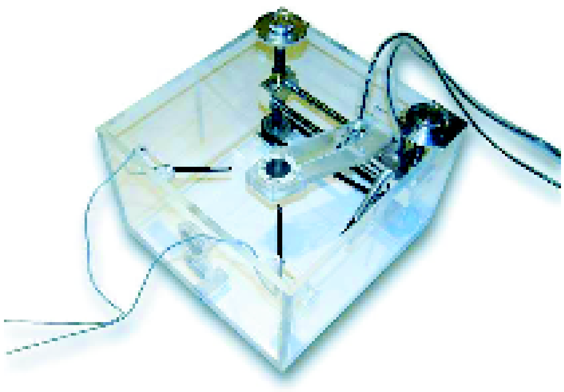


Figure 7 The Bjerke phantom for cross calibration and dose determination.

The calibration coefficient is given by

$$N_{D,W,Q_{cross}} = D_{Q_{cross}} / M_{pp,Q_{cross}} \tag{6}$$

where $\boldsymbol{D_{Qcross}}$ is the dose determined by the cylindrical chamber and $\boldsymbol{M_{pp,Qcross}}$ is the corrected charge of the plane parallel chamber. The holder of the chambers is constructed in such a way as to allow the exchange of chambers in a single movement. The chamber may be moved horizontally so that either the reference point of the cylindrical chamber or the plane parallel chamber can be on the beam axis at a reference depth.

The equation to determine dose at another electron beam quality, $\boldsymbol{Q}$, is given by

$$D_{W,Q} = M_Q N_{D,W,Q_{cross}} \frac{k_Q}{k_{Q_{cross}}} \tag{7}$$

where $\boldsymbol{M_Q}$ is the charge, and the coefficient $\boldsymbol{N_{D,W,Qcross}}$ is used together with the ratio of $\boldsymbol{k_Q}$

and k_{Qcross} which are found in Table 19 in TRS 398 [2]. $k_{Q,Qcross}$ is 1 for Q equal Q_{cross} and greater than 1 for lower R_{50}.

3.3 Low and medium energy kilovoltage x-ray beams

For low and medium energy X-ray beams, Bragg–Gray conditions do not apply. For these radiation qualities the formalism is based on direct measured air kerma calibration coefficients. The calibration at the NRPA is based on air kerma calibration at the BIPM in the HVL ranges 0.04 to 2.3 mm Al and 0.15 to 2.5 mm Cu. See StrålevernInfo 04 03 [13]. The dose is given by

$$D_{w,Q} = M_Q N_{K,Q} B_Q [(\mu_{en}/\rho)_{w,air}]_Q^{freeair} \quad (8)$$

where M_Q is the instrument charge reading, $N_{K,Q}$ is the calibration coefficient for beam quality Q, B_Q is the back scatter factor, and $(\mu_{en}/\rho)_{w,air}$ is the ratio of the mean mass energy absorption coefficients free in air. Factors and formalism are taken from TRS 277 [3]. For low energy X-rays the reference point for the plane parallel chamber is on the surface of a PMMA phantom, and for medium energy X-rays the reference point is the geometrical centre of the cylindrical chamber positioned at a depth of 2 cm in a water phantom. See Figure 8.

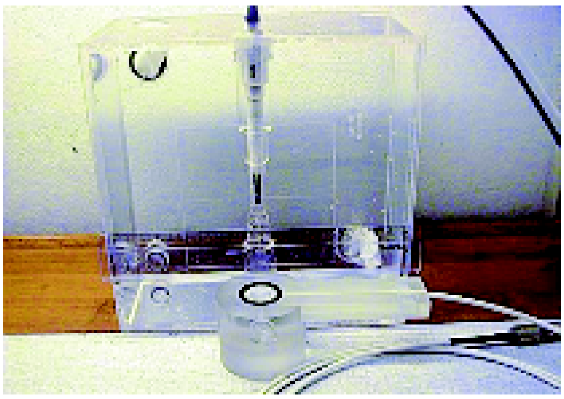


Figure 8 NRPA dose determination phantoms for low and medium energy x-rays.

3.4 The code of practice TRS 398 from IAEA

For the determination of absorbed dose to water in radiation beams, high-energy photons and electrons and x-rays used in radiotherapy, it has been decided to use the code of practice published by International Atomic Energy Agency (IAEA) [1] in 2000.

The dose in a high energy photon beam of quality Q is given by

$$D_{w,Q} = M_Q N_{D,w,Co-60} k_Q \quad (9)$$

where M_Q is the corrected dosimeter reading, $N_{D,w,Co-60}$ is the absorbed dose to water calibration coefficient for reference quality ^{60}Co gamma beam and k_Q is the beam quality correction factor.

For high energy electron beams equation (7) applies and for low and medium energy X-rays equation (8) should be used. Detailed information about the reference conditions for the determination of beam quality and absorbed dose in the different beams are given in TRS 398 [2].

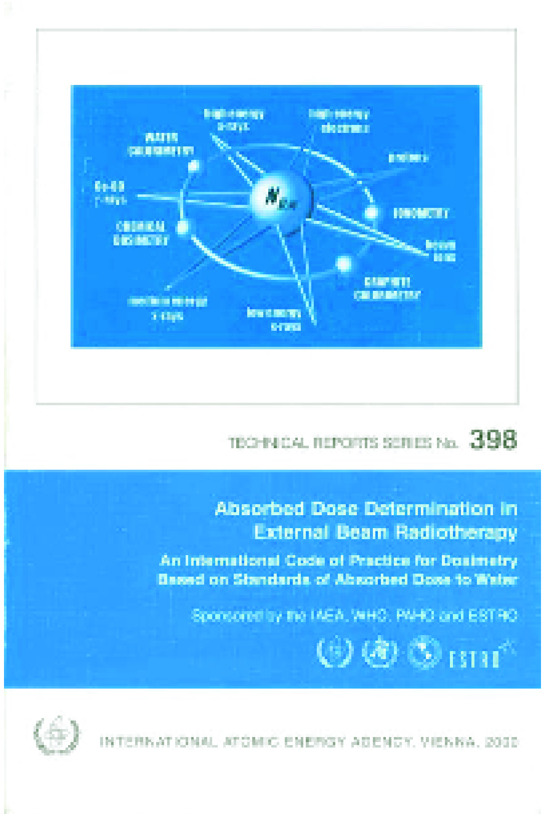


Figure 9 The Code of Practice.

4 Implementing the code

A time line for the introduction of absorbed dose to water standard and CoP is found in Figure 19.

After the establishment of the calibration capability of absorbed dose to water at the NRPA and after the CoP was published in 2000, the basis for the implementation of absorbed dose to water in the clinic was laid. Parallel to the calibration at the NRPA the lectures were prepared and instruments put together for the measuring team. The measuring team visited 7 radiotherapy centers in 2001. See map in Figures 10 and table in Figure 11.

Figure 10 Map of radiation therapy centers in Norway.

Place	Hospital	Linacs	Patients 2001
Tromsø	UNN	3(4)	700
Tr.heim	St.Olav	4(5)	965
Bergen	HUS	6	1178
Stavanger	SiR	2	497
Kr.sand	VAS	2	333
Oslo	DNR	8(+3)	2927
Oslo	UUS	3(+3)	940
Gjøvik	OSSG	2	-
Ålesund		(+2)	-
Total	7	29(39)*	7540

Figure 11 Radiation therapy activity in Norway in 2001.

4.1 The first roundtrip in 2001

Prior to the first visit to the hospitals, three NRPA chambers and one from each hospital were calibrated in a ^{60}Co gamma beam at the NRPA, in terms of the two quantities, air kerma and absorbed dose to water. The NRPA chambers were of the types NE 2571, NE 2611 and PR-06C. The hospital chambers were of types NE 2571 and Wellhöfer FC65-G (IC 70).

A lecture about the absorbed dose to water standard and TRS 398 [2] was given at every hospital in half a day on the first day of the visit.

Figure 12 Theory at DNR

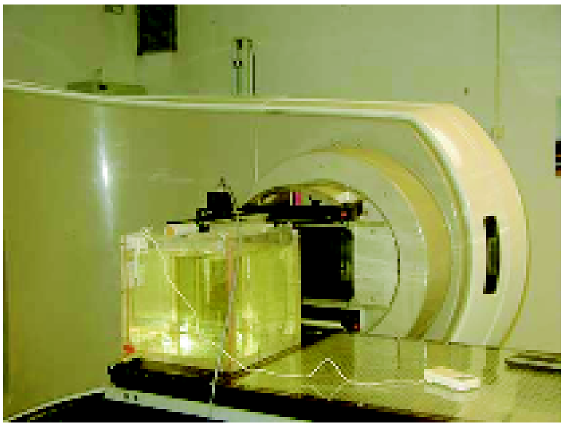


Figure 13 Dose determination in photon beams using a 30 x 30 x 30 cm^3 water phantom.

The NRPA water phantom for calibration meets the requirements given in TRS 398 [2] for the calibration of ionisation chambers in ^{60}Co gamma radiation in standards laboratories. The accuracy of the calibrations was tested in a EUROMET project [14]. For the type of chamber used by the NRPA, the calibration coefficients given by SSDLs traceable to the BIPM were consistent within 0.3 % for both N_K and $N_{D,W}$. This shows the level of uncertainty for the NRPA calibrations. In the first roundtrip, the calibration phantom was chosen for the NRPA dose determination in the high energy photon beams. See Figure 13.

4.2 Posters at the Nordic oncology meeting June 2001

Preliminary results from the first round trip were presented at the 4th Nordic Conference on Radiation Oncology in Århus. The implementation system description and the figures indicating the expected dosimetric shift in the clinical beams were presented in one poster [15]. See Figure 14. A second poster had a historical review of the Nordic co-operation in dosimetry [16].

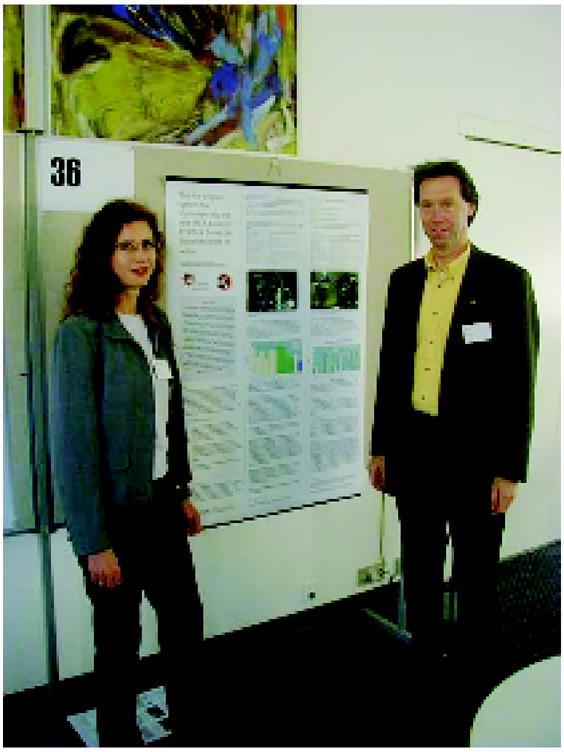


Figure 14 Poster at the 4th Nordic Conference on Radiation Oncology in Århus 2001.

4.3 Comparison at Nordic SSDLs and French PSDL

On a visit to STUK in autumn 2001, the whole Norwegian dose determination system for photon beams was compared with the Finnish on-site equipment at the University Hospital of Helsinki (HYKS). The NRPA calibrations of three of their own chambers were also compared at the Finnish SSDL. In spring 2002, two of the chambers (NE2571 and NE2611) were sent to the French Primary Standard Dosimetry Laboratory (PSDL), the Laboratorie National de Henri Becquerel (LNHB) for calibration in a ^{60}Co gamma beam and three photon beams [17] as a test of the uncertainty in the SSDL ^{60}Co calibration and a test of k_Q values taken from TRS 398 [2]. The Nordic comparison program extended to calibration of the three chambers at the Swedish SSDL in autumn 2002 and at the Danish SSDL in spring 2003.

4.4 Dosimetry audit by STUK

STUK visited three hospitals in Norway in May 2002. Ritva Parkkinen from STUK performed quality controls of CT, dose planning system and linacs. STUK has long experience in auditing and the equipment and routines for measurements' performance were good. The local dosimetry was compared with STUK and NRPA dosimetry.

Figure 15 Ritva Parkkinen from STUK (left) visiting the Ullevål University Hospital (UUS).

4.5 Cross calibrations and electron dose determinations in second and third roundtrip 2001 - 2002

The electron dosimetry could not be performed in the calibration phantom because of the horizontal beam and the 4 mm polymethylmethacrylate (PMMA) window; the large water tanks used for the hospitals' own beam data analysis measurements were therefore used in the second round trip. Setting up the water tank was time consuming, and the Bjerke phantom [12] was constructed for cross-calibration and dose determination in electron beams. See Figure 7. This phantom was used on the third trip to complete the cross-calibration of local plane-parallel chambers and electron beam dosimetry. The NRPA used waterproof FC65-G and Roos type chambers for the electron measurements.

4.6 Co-operation and the national dosimetry group

Co-operation with the medical physicists at the hospitals was part of the system for the implementation and was conditional for the SSDL taking on clinical work. The national dosimetry group monitored the work and met every third month. See Figure 16.

Figure 16 The Norwegian dosimetry group May2003

4.7 Measurements at other Nordic hospitals

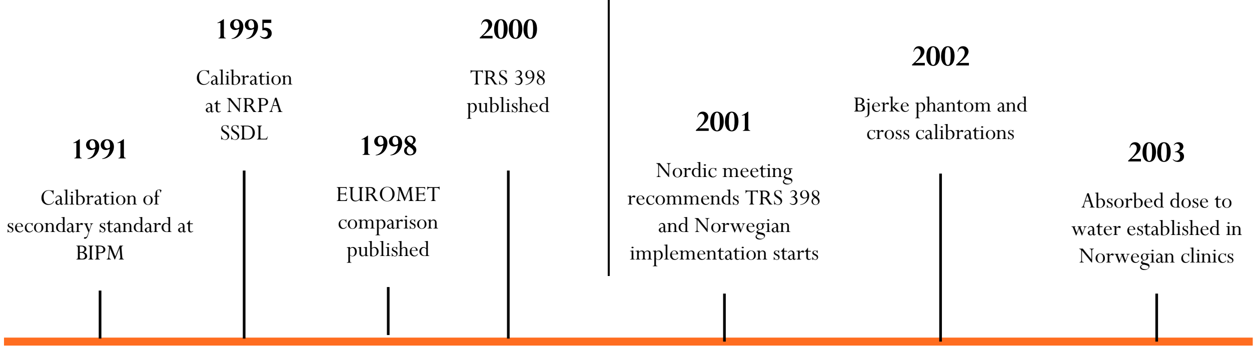
Karolinska Hospital (KS) in Stockholm and Herlev University Hospital in Copenhagen were also visited when calibration took place at the respectively SSDLs. See Figure 17 and Figure 18.

The dose in photon and electron beams were determined and compared with the dose determination of the local medical physicists. Plane parallel chambers were cross calibrated in high energy electron beams.

Figure 17 Control room at the Karolinska Hospital (KS).

Figure 18 Dose determinations and cross calibration at Herlev Hospital.

Figure 19 The time line for absorbed dose to water standard and CoP in Norway



4.8 Meetings at IAEA

IAEA formed a group developing guidelines for the implementation of TRS 398 [2] at SSDLs. The NRPA SSDL became a member of this group, which was organised as IAEA's cooperation research project (CRP). In November 2001, the first meeting took place at IAEA in Vienna. Results and experiences from the measurements in Norway were reported and discussed together with other group members' results. In November 2002, IAEA arranged an international radiation dosimetry symposium covering radiation therapy, x-ray diagnostics and nuclear medicine. The system for implementing TRS 398 [2] in Norway was presented at the meeting [18]. In June 2003, the research group met in Oslo for discussion and reporting about the implementation at SSDLs. The group will work out guidelines for the implementation of TRS 398 [2] at the SSDLs. The recommendations will be published in an IAEA TECDOC.

5 Results and discussion

5.1 Absorbed dose to water calibrations

The SSDLs of Finland, Sweden and Denmark and the PSDL of France determined the absorbed dose to water calibration coefficients, $N_{D,W}$, for two chambers of type NE 2571 and NE 2611. Compared with the NRPA calibration, the Finnish calibration in a ^{60}Co beam agreed within 0.3% and the French calibration within 0.4%. The results from the calibration in ^{60}Co beams of two chambers are given in Figure 20. The calibration coefficients determined at the labs are within one standard deviation of the given uncertainties, which is 0.5 % for the SSDLs and 0.6 % for LNHB. The results from dose determinations at clinical beams are also given. It seems from measurements that the dose agreement is better when the comparison is among SSDLs determinations, as it is for the Helsinki University Hospital (HYKS).

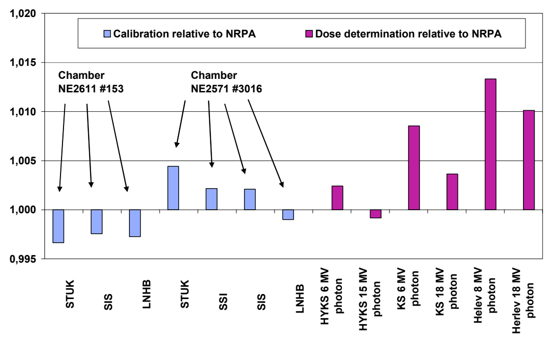


Figure 20 Comparison of absorbed dose to water calibrations and determinations. Two chambers are calibrated at three SSDLs and one PSDL. Dose determined at three hospitals in the North outside Norway.

From the calibrations at NRPA since the beginning of 2001, the $\boldsymbol{C_K = N_{D,W}/N_K}$ factor is determined. See Figure 21. $\boldsymbol{C_K}$ indicates the calibration reliability and show the behavior of the chamber in the water phantom versus free air measurements.

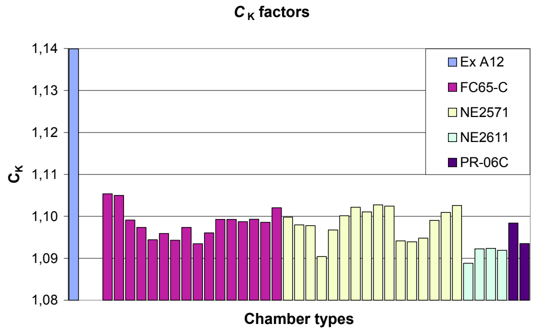


Figure 21 Variation in C_K factor as a function of chamber types.

5.2 Dosimetry in photon beams

The calibration phantom was used on the first round trip to determine the absorbed dose to water based on the air kerma standard in 16 clinical photon beams. At the same time, the local medical physicist was asked to measure and determine the photon dose following the same protocol and using local equipment and calculations.

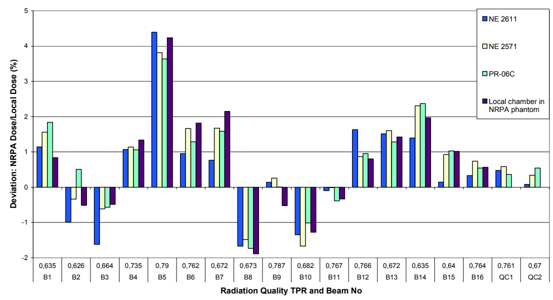


Figure 22 The deviation (%) of the NRPA dose determination (TRS 277) from the local dose determination (TRS 277) for different photon beam qualities $TPR_{20,10}$. The baseline is dose measured with local equipment. For QC1 and QC2, STUK dose determination is the baseline. For each B and Q, one bar represents measurements from one chamber.

The dose in photon beams was first determined on the basis of TRS 277 [3]. The dose was normalized to the local dose determination. Results for all photon beams from the dose determinations in the first round trip in Norway and the two beams (QC1 and QC2) used for quality control for the SSDL's site visit equipment in Finland are given in Figure 22. For the 16 photon beams (B1–B16) the deviations between the hospitals' and the SSDL's absorbed dose to water determinations in terms of TRS 277 [3] were in the range of –1.9 % to +4.4 %. Most of the deviations were explained by the local implementation of TRS 277 [3] and the use of plastic phantoms. The lack of recent calibrations of thermometers, barometers and electrometers caused minor deviations. The hospitals and the NRPA worked out together the reasons for the deviations, and corrective actions were taken by the hospitals.

Site visit equipment from the NRPA and STUK were compared at HYKS. It can be seen from Figure 22 that NRPA and STUK dose determinations in QC1 and QC2 beams agreed within 0.6 %. The uncertainty of the NRPA photon determination is stated to be 1.0 %, with a coverage factor of 1, and the result of the comparison is within the uncertainty.

By correcting for displacement of the effective point of measurement, p_{dis}, and linking the data in the photon dose worksheet of TRS 398 [2] to the worksheet of TRS 277 [3], it was possible to predict the historical dose shift for all 18 photon qualities. See Figure 23. The figure shows that the dose in photon beams based on TRS 277 [3] and a ^{60}Co air kerma standard, has been overestimated by 1.0 % – 1.5 % as is now determined using TRS 398 [2] and a ^{60}Co absorbed dose to water dosimetry standard.

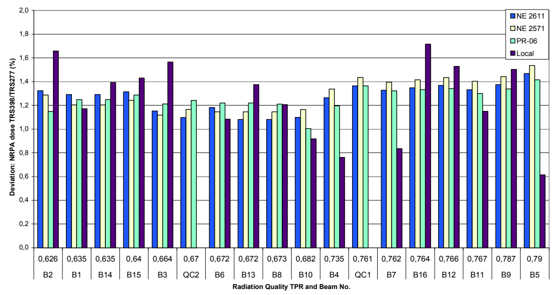


Figure 23 Theoretical determination of relative dose in a NRPA phantom ((TRS 398 dose)/(TRS 277 dose)) (%).

5.3 Validation of k_Q for photon beams

TRS 398 [2] recommends direct measurement of k_Q for a set of beam qualities at a PSDL for a particular chamber. This is the basis of the first and second recommendations given in the implementation chapter. The third recommendation is to use a theoretical k_Q from TRS 398 [2]. Our two chambers had k_Q determined by the French PSDL (LNHB) for a set of beam qualities. The LNHB calibrated the chambers for photon qualities $TPR_{20,10}$ equal to 0.675, 0.749 and 0.784 [17]. The uncertainties of the absorbed dose to water coefficients were 1.1%, with a coverage factor of 1. The k_Q from the LNHB for the three qualities were 0.992, 0.980 and 0.970 for NE 2571 No. 3016 and 0.995, 0.982 and 0.972 for NE 2611 No. 153, respectively. The deviation in k_Q between these and the theoretical values from TRS 398 [2] are +0.1, +0.4 and +0.4% for NE 2571 and –0.3, –0.2 and –0.2% for NE 2611. This is in accordance with the work of Seuntjens et al [19], wherein a maximum difference between theoretical and experimental $\boldsymbol{k_Q}$ factors of 0.45 % was observed.

In Figure 23, the introduction of k_Q from the LNHB would change the level between the first and second bars for all B and Q – 0.6 % and +0.4 %, respectively, for all beams (i.e. the change of k_Q would decrease the determined dose for NE 2611 and increase it for NE 2571).

5.4 Cross-calibration in electron beams

On the second set of visits, this time for electron beams, priority was given to the cross-calibration of the hospital plane-parallel chambers in the highest energy electron beam and measurements of absorbed dose to water in different electron beams in accordance with TRS 398 [2]. All linacs were in clinical use and setting up the local water tanks was time consuming. Local determination of dose was therefore given low priority. This time the absorbed dose was compared with the treatment unit's monitor calibration determined by the hospital earlier.

The cross calibration of the NRPA Roos chamber was performed at each site to record the stability of the calibration in the electron beams. The standard deviation for the absorbed dose to water coefficient ($\boldsymbol{N_{D,w}}$) corrected to the same electron beam quality was less than 0.3%. The uncertainty in cross calibration for the

Bjerke phantom, (see Figure 7) is stated as 1.5%, with a coverage factor of 1.

5.5 Dosimetry in electron beams

The determination of absorbed dose to water in high energy electron beams was before 2000, performed in plastic phantoms except for one hospital. The correction factors for density, electron fluence and chamber/phantom effects are uncertain and dose deviations were expected.

The results from absorbed dose to water measurements for high energy electron beams from NRPA dose determinations in the second and third roundtrip are shown in Figure 24. Compared to TRS-398 dosimetry the nominal doses given by the linacs were on average overestimated by 0.6 % and the dose deviations were –2.3 to + 4.6 %. The uncertainty of the electron measurements was 1.5 % with a coverage factor of 1.

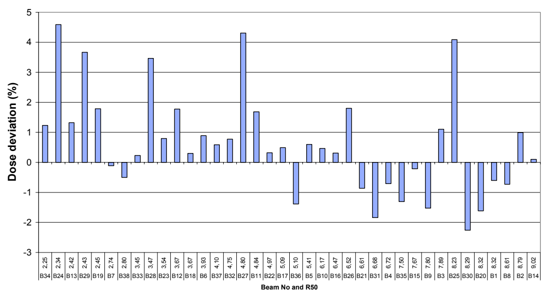


Figure 24 NRPA dose determinations in electron beams compared to 100 MUs.

5.6 Local implementations

The first roundtrip to the hospitals showed a need for waterproof ionisation chambers, both cylindrical and plane parallel. There was a lack of water phantoms for precise positioning of ionisation chambers in water. In the following paragraphs, a report from each hospital with respect to adaptation of equipment/ methodology and their local experience is presented.

5.6.1 UNN

At the University Hospital of North Norway, the transition of the dosimetry protocol from TRS 277 [3] to TRS 398 [2] has been delayed because the installation of new linacs has been postponed. The new linacs are calibrated according to TRS 398 [2]. Calibration of the two old ones will be done according TRS 398 [2]. At the same time the reference point for calibration is going to be changed from D_{max} employing source surface distance (SSD) equal to 100 cm to source chamber distance (SCD) equal to 100 cm. TRS 398 [2] recommends calibration in water phantom and Wellhöfer Blue Phantom (WBP) will be used for reference calibration both for photons and electrons. For routine use, a small water phantom developed and manufactured at the Norwegian Radiumhospital will be used. See Figure 30. For electrons a PMMA phantom together with NACP plane parallel chamber will be used for routine measurements. Electrons will also be calibrated to give a dose of 1.00 Gy at dose maximum with an SSD = 100 cm and a setting of 100 monitor units (MUs).

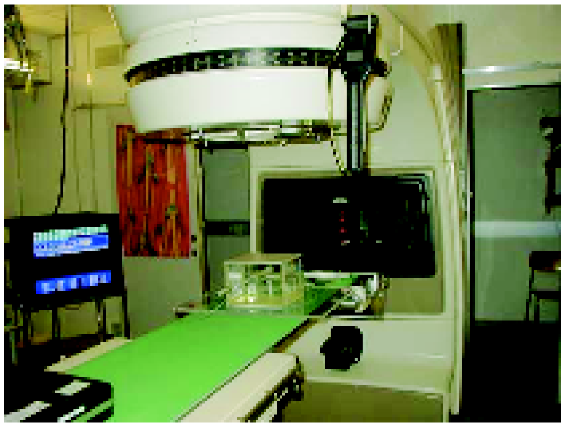


Figure 25 Water phantom TRS 277 at UNN.

Electrons: Depth ionisation curves will be taken in the WBP with a NACP 02 plane parallel chamber and converted to depth dose curves according to OmniPro program and the reference depth will be chosen according to the protocol. Routine measurements will be done with a plane parallel chamber in a Perspex phantom at the nearest depth in mms of the reference depth in water. A user factor linking the situation in the reference condition to the situation in the routine measurement condition will be introduced. Eventually, a solid water phantom can be used.

Photons: As it was mention before, for routine measurements of photons a water phantom from DNR and no extra user factor is needed. Alternatively, a solid water phantom and then a new user factor must be introduced.

5.6.2 St. Olavs Hospital

The TRS 398 [2] protocol for determination of absorbed dose to water was implemented at St. Olavs Hospital during spring/summer 2003. This protocol replaced the former determination of absorbed dose based on the IAEA protocols TRS 277 [3] and TRS 381 [4].

The TRS 277 [3] and TRS 381 [4] protocols were implemented locally by using *Solid Water* and *Plastic Water* as the phantom material, both for photons and electrons. The photon dosimetry was based on calibration at the depth of maximum dose for the given energy, with the chamber positioned at the isocentre. This implied that radiation with 100 MU given with a 10x10 cm^2 field with the point of maximum dose at isocenter resulted in 1 Gy at this point. Photon energies were matched between twin accelerators and average values (stopping power, etc) were used for calibration.

Electron energies were calibrated according to TRS 381 [4] at the point of maximum dose with standard SSD = 100 cm for the newest accelerators, SB5 and SB6, and SSD = 95 cm for the old accelerator, SB3. Radiation with 100 MU for electrons with the 10x10 cm^2 applicator with the standard SSD gave 1 Gy at the point of maximum dose. Depth dose correction factors were based on measurements done with diodes. Electron energies were matched between twin accelerators and average stopping power and depth dose correction factors were used for calibration.

The new determination of absorbed dose to water is implemented according to the TRS 398 [2] protocol. The Wellhöfer Blue Phantom is used for reference calibration, and locally produced holders fix the ionisation chambers in the water tank. A smaller water tank will be provided by the hospital for future reference calibrations. For routine calibrations *Solid Water* and *Plastic Water* will be used as phantom material. For this purpose it has been established conversion factors relating measurements in water to phantom material (*Solid Water* and *Plastic Water)*.

For photon calibration the TRS-398 recommendation is used measuring at 10 cm depth with a 10x10 cm^2 radiation field and SSD = 90 cm. The photon dosimetry (dose calculation tables) is based on a TMR-formalism requiring 1 Gy at the point of maximum dose with a 10x10 cm^2 radiation field and SSD = 100 – z_{max} . In order to obtain this a TMR – correction factor is used, and small differences between energies are taken into account. A cylindrical ionisation chamber of the type FC65-G produced by Wellhöfer for photon calibration is used.

For electron calibration according to TRS 398 [2], a standard SSD = 100 cm for the new accelerators is being used. However, for old accelerator SSD = 95 cm is used as standard. Radiation with 100 MU with the 10x10 cm^2 applicator gives 1 Gy at the point of maximum dose with the standard SSD. Depth ionisation curves have been measured with a plane parallel ionisation chamber (NACP-02) according to TRS 398 [2]. These curves are converted to dose using the protocol AAPM TG-51. The same ionisation chamber, cross-calibrated in the clinic's 18 MeV electron beam, is also used for dose calibration of the electron beam. Despite the energy matching, there are small differences in depth dose characteristics and these are taken into account.

For calculation and registration of calibration measurements a computer program called “Kalprog” is developed at St. Olavs Hospital. This program was modified to follow the new protocol.

The ratios between the TRS-277/381 based dosimetry and the TRS 398 [2] based dosimetry, locally implemented calibrations varies from 0.990 to 0.974 for photons and 0.985 to 0.960 for electrons. The differences between the protocols include not only the expected changes because of the two formalisms, but also differences due to local implementations of phantom material and measuring geometry for photon and electron beams. However, the largest discrepancies observed for electrons are mostly due to the slight differences in the depth dose curves measured with diodes (local implementation of TRS 381 [4]), and those measured with an ionisation chamber. The discrepancies are also due to averaging of depth dose data used in the implementation of TRS 381 [4], while the implementation of TRS 398 [2] takes into account the individual electron energies. The largest discrepancy between TRS 381 [4] and TRS 398 [2] is 0.975 for an electron beam.

5.6.3 ÅS

Two linear accelerators will be installed at Ålesund Hospital (ÅS) in the early fall 2003. The accelerators will be calibrated in corresponding with the instructions given in TRS 398 [2]. Ålesund Hospital will use the Kalprog [20] program for calibration and documentation.

5.6.4 HUS

At Haukeland University Hospital (HUS), absorbed dose determination during the last two decades has been performed in plastic phantoms (see Figure 26) according to the NACP [10] (1981) and TRS 277 [3] (1987) protocols. Most of the measurements have been done with a parallel plate ionisation chamber both for electron and photon radiation qualities.

Figure 26 The polystyrene phantom in use at HUS.

Materials and method: In order to fulfil the requirements of TRS 398 [2] the plastic phantoms must be expelled and water is going to be used. Besides, for photon beams the utilisation of parallel plate chambers should be abandoned in favour of cylindrical chambers. A handy water phantom for the purpose of routine dose determination was not available at the institution. So, in order to keep the routine dosimetry procedure as close as possible to the established method with polystyrene phantoms the decision was, during a transition period, to relate the usual routine method to a method exactly matching the TRS 398 [2] method. A link between the two set-ups was made throughout using a fixed external monitor chamber in the beam for the two subsequent measurements in either water or plastic phantoms. Thus a correction factor for the routine method was found. After consulting the NRPA, intervals of twelve months were suggested as appropriate between such reference measurements in water phantoms. For routine dosimetry, intervals of five weeks will still be kept.

Photons: As reference chamber, a new waterproof cylindrical Farmer type FC65-G from Wellhöfer was selected. The chamber was calibrated in water at the SSDL at NRPA, Oslo, in May 2001. A holder for the ionisation chamber was used as a fixation inside the Wellhöfer water phantom. Then, by means of software and computer controlled stepper motors, the chamber could be quickly positioned at the isocentre. The water depth was checked with sticks designed to indicate the correct level of the water surface in the phantom [15].

Electrons: A new waterproof Scanditronix NACP plane parallel chamber was selected as reference for the electron beams. It was cross-calibrated against the FC65-G using the clinic's 22 MeV electron beam. Likewise the cylindrical chamber, also the NACP chamber could be used for measurements in the WBP. See Figure 27.

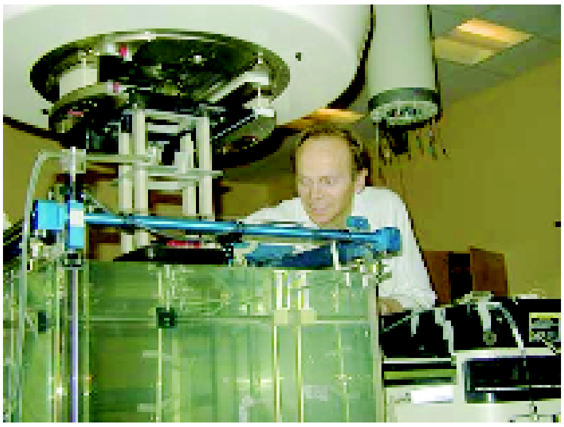


Figure 27 Measuring in WBP at HUS.

Transition from TRS 277 [3] to TRS 398 [2]: Results from measurements according to both the TRS 277 [3] and the TRS 398 [2] protocols were compared. Measurements according to the TRS 277 [3] were performed with the dosimeter positioned at the effective point of measurement in clear polystyrene phantoms without density corrections. Measurements according to the TRS 398 [2] were done as described in the protocol. Dose calculations for both protocols were executed with the help of the clinic's own dosimetry PC-tool for external radiation therapy equipment "Dosimetry 4.0" [20] and subsequently verified by the Excel spreadsheets published by the IAEA. The largest dose discrepancies were observed for the three high energy photon beams 10, 15 and 25 MV; TRS 277 [3] vs. TRS 398 [2] ratio ranging between 0.965 and 0.980. For all the other radiation qualities shifts were detected within the expected ratio interval 0.985 – 0.990.

Clinical implications: After the switch to the TRS 398 [2] protocol was completed an internal note was written to the Head of the oncology department with a statement of the observed dose shifts and the potential low risk of long term clinical consequences.

QA: The clinic has since 1998 participated in the ESTRO/EQUAL quality audit. Immediately after the transition to TRS 398 [2], the 25 MV and 15 MV beams were checked by TLD which was mailed back to the EQUAL laboratory in Paris. Results showed that the hospital stated higher dose values than what were found by TLD dosimetry of the EQUAL laboratory: + 0.4 % for the 25 MV beam and + 3.1 % for the 15 MV beam.

During the periodic quality control procedures, some extra workload has been imposed through the introduction of the new water based dosimetry protocol. Two technical engineers work during afternoons to execute the dose determinations at regular intervals, and their session reports are signed electronically by a supervising physicist. The following day the reference dosimetry will however, impose something between 45 and 60 minutes overtime per radiation quality checked, until measuring in polystyrene is ceased.

5.6.5 SiR

The Rogaland Central Hospital (SiR), Department of Radiotherapy in Stavanger started treating patients in December 1998. For the absolute dose calibration of the machines, a phantom material composed of *Virtual Water* has been used since 1998 to the present. In addition to the phantom, a cylindrical Farmer type ion chamber (NE 2571) for photons, and a plane-parallel chamber (NACP 02) for electrons have also been used for calibration. TRS 277 [3] and 381 [4] protocols were followed.

Figure 28 Measuring team at SiR.

Photons: With the release of the new IAEA protocol, TRS 398 [2], attention was directed to the fact that the density of *Virtual Water* was 1.03 g cm^{-3}, which was different from water. Instead of the reference depth for photons in *Virtual Water* of 10.2 cm (0.2 cm extra according to TRS 277 [3] for the correction of the effective point of measurement in the cylindrical ion chamber), the equivalent depth in water was 10.5 cm. These numbers were also seen in the results of the measurements at the NRPA dosimetry audit in 2001. It was then discovered that the above mentioned measurements had been performed with the wrong polarity of the voltage. In total, this resulted in an overdose of 2 % for both photon qualities. A correction was soon calculated where the depth in *Virtual Water* was subsequently changed to 9.9 cm.

In late 2001, TRS 398 [2] for photons was implemented. At that time the department did not have a waterproof cylindrical ion chamber for reference dosimetry. The measurements were then performed with the NE 2571 type chamber in *Virtual Water*, with a depth of 9.7 cm. In TRS 398 [2], the correction for the effective point of measurement is included in the correction factor k_Q. The difference between the old and new protocol for 6 MV was 1.1 % and for 15 MV was 1.2 %.

After acquiring a waterproof Exradin A12 Farmer chamber, calibrated at the SSDL of NRPA, the department was able to measure the dose in a water tank, the WBP however, for convenience purposes, the monthly QA of absolute dosimetry was decided to be performed in *Virtual Water*. A direct comparison was made between *Virtual Water* and the water tank. Absolute measurements with the water tank are made at least once a year.

A 10 cm long metal string [21] is used to verify the distance from the water surface to the centre of the cylindrical chamber. In one end it is shaped to fit around the top of the chamber and a cork is attached to the other side. Hence the other end is directed towards the water surface when the chamber is in water. The centre of the chamber can then accurately be positioned at 10 cm depth.

Electrons: At the NRPA dosimetry audit in December 2001, the NACP plane-parallel chamber was cross calibrated against a cylindrical chamber in the highest electron energy, 22 MeV. In 2002, when the measurements for implementing TRS 398 [2] for electrons were made, a leakage in the NACP chamber was discovered and water entered to the chamber. At that time the measurements were instead made with the Exradin chamber. However, an accurate way for determining the depth for this chamber was not prepared, and the measurements had an unacceptable fluctuation. The Exradin chamber had not been calibrated at the SSDL of NRPA and did not have the $N_{d,\,air}$ factor. Hence, it was not possible to compare the two protocols with the same chamber. However, measurements made with the NACP chamber that were conducted prior to the water tank measurements, indicate a difference of ~1 %.

As for photons, the department decided to do the routine QA in *Virtual Water* and use an additional factor, k_{user}, to correct for the difference in the set-up.

5.6.6 VAS

The Centre of cancer treatment at Sørlandet Hospital, a satellite to DNR in Oslo, started to treat patients in February 2001. The department possesses two Siemens Primus linear accelerators.

When the machines were installed in autumn 2000, the TRS 277 [3]/TRS 381 [4] protocols were first established. After one year the TRS 398 protocol was implemented and the machines were adjusted: first, the photon energies (6MV and 15MV) in December 2001 and then the electron energies (6, 9, 12, 15, 18 and 21 MeV) in November 2002. Prior to the TRS 398 implementation, the department was visited by the NRPA, who validated the local TRS 277 [3]/TRS 381 [4] dosimetry and advised the physicists on how to measure the absorbed dose to water, hence providing a convenient quality control during the new protocol implementation.

Photons: For the Photon dosimetry the FC65-G cylindrical farmer chamber, the Dose 1 electrometer and the W 33 water phantom from Wellhöfer were used. The phantom allowed placing the ion chamber in discrete steps of 5 mm when irradiating horizontally towards the phantom surface window (3 mm). A PMMA chamber sleeve was used to keep the chamber dry. The source to phantom wall distance was 900 mm, the source to isocentre distance was 1000 mm and the field size was 10 cm x 10 cm. With the TRS 277 protocol, the department already had established the TRS 398 dosimetry set-up with a correction factor for the ion chambers effective point of measurement. In that manner the TRS 398 photon implementation was reduced to a calculation exercise. The new calibration coefficients were provided by the NRPA, and quality factors and appropriate correction factors demanded by the CoP were determined from TRS 398 [2].

Three different programs, based on the same algorithm, were used to calculate the absorbed dose to water: the IAEA TRS 398 [2] worksheet, an Excel based program from The Norwegian Radium Hospital and the Dosimetry control 4.0 [19] made at the Haukeland University Hospital. Disregarding the day-to-day dose variations on the treatment units, the dose was adjusted according to the calculated expectation value, which was a lowering of the machine output of 1.1 % for 6 MV and 1.0 % for 15 MV, respectively.

Figure 29 Preparing for electron beam measurements at VAS.

Electrons: With the former TRS 381 [4] protocol the electron dose was measured with a plane-parallel chamber in a solid water phantom. The dose was measured at the dose maximum, with a 15 cm by 15 cm electron applicator, and a source to surface distance (SSD) of 1000 mm.

With the new TRS 398 [2] protocol, the measurements had to be performed in water at depths that could be adjusted in fractions of millimetres. The electron measurement depths were derived from depth dose scans ($\boldsymbol{R}_{50}$, the depth where the absorbed dose is 50 % of its value at the absorbed dose maximum). For the depth dose scans the blue phantom (WBP) and the controller CU 500 E electrometer from Wellhöfer and the waterproof NACP 02 plane-parallel chamber from Scanditronix were used. For the absolute dosimetry the electrometer was replaced by the Dose 1 electrometer from Wellhöfer.

The NACP 02 chamber was cross-calibrated against the FC65-G in the clinic's 21 MeV ($\boldsymbol{R}_{50}$ = 8.43 cm) electron beam during the NRPA visit.

Depending on the electron energy and disregarding the day-to-day dose variations on the treatment units, the absorbed dose was reduced between 0.7 and 1.3 % when adjusting between TRS 381 [4] and TRS 398 [2] and their two different measurement set-ups.

To be able to make a quick QA-check on the daily electron absorbed dose to water calibration, a measurement set-up based on solid water and NACP 02 chamber was established. The measurement depth in solid water was set to the nearest millimetre as compared to the calculated TRS 398 [2] electron measuring depths in water.

Experiences: During the TRS 398 [2] protocol implementation and the visit from the NRPA there was a deviation when comparing atmospheric pressure (0.5%) and some confusion about what correction factors to use for the cylinder chamber sleeve and the phantom window.

It was difficult to adjust the chamber depth to the water surface when using the NACP 02 chamber in the WBP. For this purpose NRPA provided a precisely manufactured "pointer" [21] that, when mounted on top of the chamber, made possible to make an exact adjustment of the distance from the effective point of measurement to the water surface.

The department will benefit (in QA and accuracy) from buying a smaller water phantom with a continuous depth adjustment to do the

TRS 398 [2] electron absorbed dose to water dosimetry.

5.6.7 DNR

The Norwegian Radiumhospital (DNR) has 8 accelerators in clinical use, 5 of them with dual photon energies and electrons in all, 13 photon and 26 electron beams. The TRS 398 [2] was implemented for all high energy radiotherapy photon and electron beams at the hospital in the period April 2002 to March 2003.

Photon beams: TRS 398 [2] calibration in photon beams were carried out with the Wellhöfer Blue Phantom (WBP) and a watertight ionisation chamber of Farmer type (FC65-G).

A more handy sealed water phantom will be used for routine measurements. The outer dimensions of this phantom are 30.0 x 30.0 x 15.0 cm^3 with a beam entrance window made of 3 mm polystyrene. See Figure 30. The chamber sleeve, with axis at 10.0 cm depth, is made of PMMA. The thickness of the sleeve wall surrounding the active volume is less than 1.0 mm.

Based on parallel measurements in WBP, a factor correcting for plastic walls and possibly inexact chamber position is established.

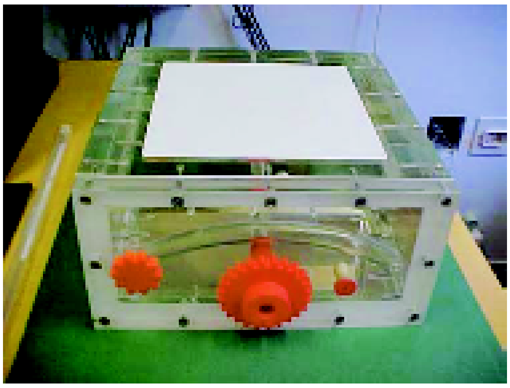


Figure 30 The DNR photon calibration phantom, 30.0 x 30.0 x 15.0 cm^3. A beam entrance window made of 3 mm polystyrene and a chamber sleeve with axis at 10.0 cm depth, whose wall is made of less than 1.0 mm PMMA.

Electron beams: All electron qualities were calibrated with WBP and a waterproof Roos chamber (PPC 40). This particular chamber was chosen due to its sturdy construction. As for the annual inspections, percentages depth dose (PDD) curves were measured for all electron qualities and checked against the original beam data. The PDD at z_{ref} was defined for each beam quality.

Figure 31 Polystyrene phantom for routine measurements in electron beams.

The outputs were then adjusted in accordance with the TRS 398 [2] to 1.00 Gy per 100 MUs at dose maximum. Immediately afterwards, the measurements were repeated with a plastic phantom consisting of polystyrene sheets with thickness' corresponding to the reference depths. See Figure 31. In this way correction factors for all electron beams were established for this simple phantom, which will be used for routine quality assurance measurements.

Phantoms: TRS 398 [2] recommends a homogeneous water phantom as reference medium for dose measurements. WBP with waterproof chambers fulfil this requirement and will be the hospital's reference dosimetry system. Setting up the WBP, however, is an elaborate and time-consuming procedure. Dose determinations in this phantom will probably only be carried out in connection with the annual quality control where the PDDs are checked.

Figure 32 The Phantom (WP-34).

For the periodic quarterly calibrations and more occasional measurements initiated from the daily morning checks, the WBP will be used in addition to the simpler phantoms mentioned. The WBP requires horizontal beam, but can be used for both photon and electrons. In order to get a reliable and precise positioning, the scales on the WBP are slightly modified in accordance with the chambers we are using.

5.6.8 UUS

The Ullevål University Hospital (UUS) started with high energy radiation therapy in 1972 and has now three linear accelerators. The new international code of practice, TRS-398 [2], was implemented for three photon beams during the period February 21st - June 5th, 2002. The new code of practice was implemented on the March 18th, 2002, for five electron beams.

Figure 33 Ståle Ølberg placing the water phantom in the beam at UUS.

A water phantom with discrete positioning (steps of 5 mm) of the ionisation chamber was used for the calibration. The depth closest to z_{ref} was chosen. The $k_{Q,Qint}$ (eq. 30 in TRS 398 [2]) was adjusted to the chosen chamber depth by a multiplication of a ratio of the two corresponding stopping power ratios given in Table 20, TRS-398 [2].

Equipment:

Electron-chamber: PTW Roos

Photon-chamber: NE 2571 Farmer

Electrometer: PTW Unidos

Water phantom: PTW, Type 4322

Horizontal beam direction was used during calibration. The water-equivalent thickness of the window was taken into account.

5.6.9 SI Gjøvik

The radiotherapy clinic at Sykehus Innland Gjøvik (SI Gjøvik) was opened in August 2002 as a satellite to DNR in Oslo. The clinic has two linear accelerators (Siemens Primus) with high energy photons (6, 15 MV) and electrons (6, 9, 12, 15, 18, 21 MeV). With the support from DNR it was decided to use the TRS 398 [2] as dosimetry protocol from the beginning.

Figure 34 Odd Harald Odland doing the acceptance test at SI Gjøvik.

For the dosimetry of the photon beams two cylindrical ionisation chambers Farmer FC65-G and two electrometers Wellhöfer DOSE 1 are used. The ionisation chambers are used as hospital reference chambers and they were calibrated to absorbed dose to water in a ^{60}Co gamma beam at the NRPA in 2002. The dosimetry is performed using WP-34. The phantom is irradiated horizontally through a thin entrance window, water equivalent 2.4

mm, and a metric ruler and a movable bridge-type tube holder mounted on the top of the tank determine the depth in water. The ionisation chambers are waterproof and they are inserted into an adapter fixed to the movable bridge. The dosimetry in the water phantom is done quarterly and for more frequent dosimetry a solid water phantom is used.

The dosimetry of the electron beams is performed with two plane-parallel ionisation chambers Wellhöfer NACP-02 and the two electrometers Wellhöfer DOSE 1. The ionisation chambers are used as hospital reference chambers and they were cross-calibrated locally by the NRPA in the Bjerke phantom [12] in order to obtain the calibration factor for absorbed dose to water in the 21 MeV beam, R_{50} = 8.42 cm, from one of the accelerators. The ionisation chambers are waterproof and the dosimetry is done vertically irradiating in WBP. The chambers are positioned in a holder electrically movable in all three geometrical directions. The position in water of the reference point of the chamber is controlled by computer software Wellhöfer OmniPro™, with an accuracy of 0.1 mm. For each energy, depth-dose measurement is used to calculate z_{ref} and $k_{Q,Q0}$ according to TRS 398 [2]. The dosimetry in the water phantom is done quarterly.

5.7 Reports for photon beams

It can be seen from the NRPA dose determinations (first roundtrip) in Norway that the air kerma standard and TRS 277 [3] has overestimated doses for high energy photons in accordance with TRS 398 [2] by 1.0 to 1.5%. The medical physicists reported in 2002-03 the determined dose shift to NRPA. Relative to the absorbed dose to water based dosimetry, reports from hospitals for 43 clinical photon beams show that the air kerma based photon dosimetry has overestimated the dose, as an average, by +1.0%. See Figure 35.The range is -1.4 % to +3.6 %. In Figure 36 the frequency of the percentage change for photon beams is shown.

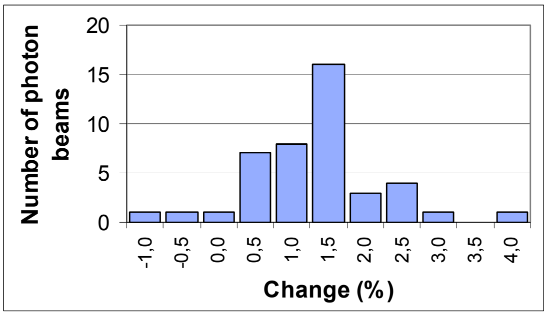


Figure 36 Numbers of photon beams changed in intervals of 0.5 %.

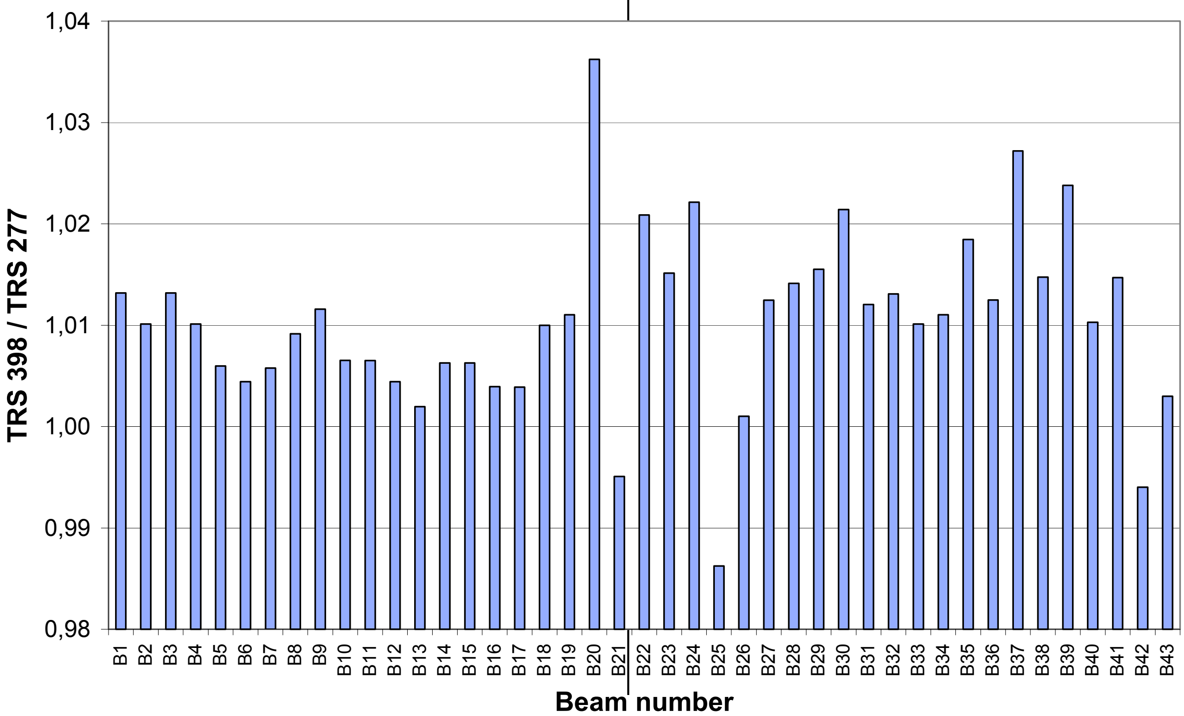


Figure 35 Reported dose ratio for 43 photon beams

5.8 Reports for electron beams

Reports from hospitals show that relative to the absorbed dose to water based dosimetry, the air kerma based photon dosimetry has overestimated the dose, as an average, by 1.5 %. See Figure 38. The range is -1.2 to + 4.2 %. In Figure 37 the frequency of the percentage change for electron beams is shown.

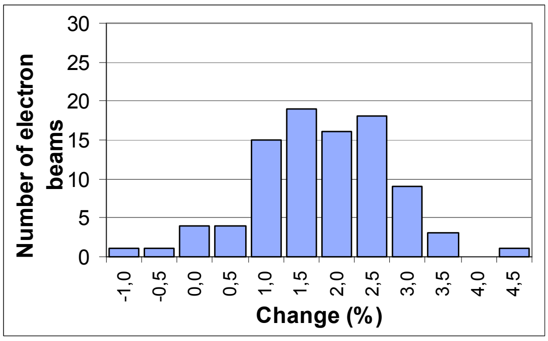


Figure 37 Numbers of electron beams changed in intervals of 0.5 %.

5.9 Safety considerations

Because the $N_{D,w}$ calibration coefficients are 13% greater than the N_k coefficients, there is a potential for errors if the wrong coefficient is inadvertently used. The system described for implementing the absorbed dose to water standard and code of practice in radiotherapy has minimized any chance of this occurring and has disseminated the new dosimetry approach in a consistent way to all clinics. Medical physicists at the hospitals welcomed the visits and the clinical dosimetry has been improved. The measurements showed a need for audits to control the local implementation of a code of practice in dosimetry.

5.10 Dose delivery – before and after change of CoP.

The dose output in the beams, when implementing TRS 398 [2], is of interest for the evaluation of medical consequences. From the data of the first roundtrip, the beam dose data from 16 photon beams are available. See Figure 39. One standard deviation for the delivery of one fraction dose using TRS 277 [3] was 1.9 % for the 16 photon beams, two or more beams from each center. The average deviation from NRPA dose determinations was (1.3 ± 1.1) % higher than the assumed administrated dose, and the range was + 3.8 % to – 1.4 %. The uncertainty in the NRPA dose determinations is estimated to be 1.0 % with a coverage factor of 1. This was the situation before 2001 when TRS 277 [3] was in use.

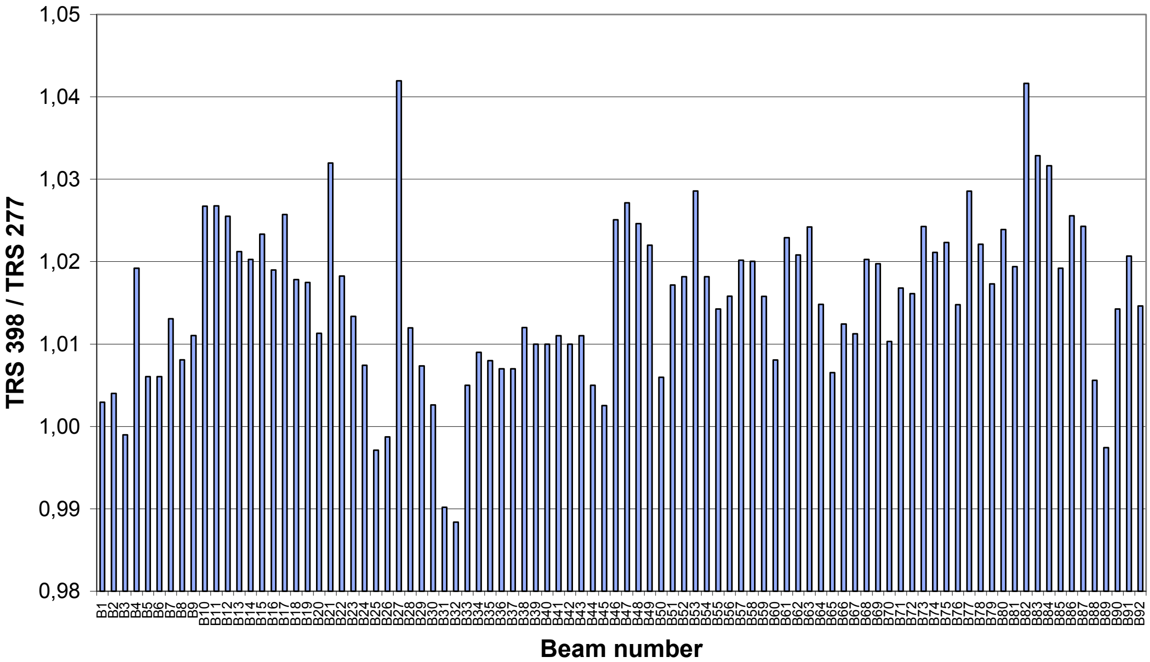


Figure 38 Reported dose ratio for 92 electron beams.

For a specific beam, the target volumes have been exposed to either more or less dose according to information given for the 16 beams in Figure 39. For high energy electron beams, the results are given in Figure 24. In the NRPA dose determinations the TRS 398 [2] were followed and the linacs have been TRS 277 [3] or TRS 381 [4] dose calibrated. The average deviation between the NRPA dose determinations and the dose delivered in the different 38 electron beams, four or more beams from each center, and the monitor units given by the linac were (0.6 ± 1.5) % higher than the assumed administrated dose, the range + 4.6 % to – 2.3 %. One standard deviation for the delivery of one fraction dose using TRS 277 [3] or TRS 381 [4] is 2.2 %.

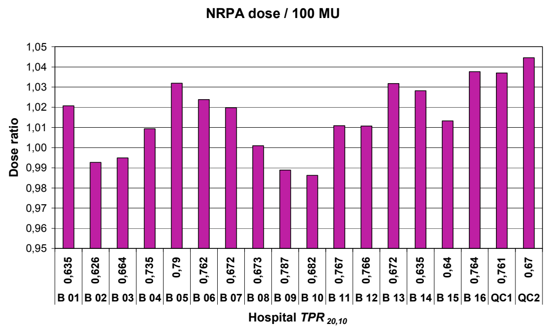


Figure 39 NRPA determined dose for 100 MU in photon beams.

For the assessment of patient target dose before and after the implementation of TRS 398 [2], the hospitals have reported dose determinations. The average dose levels for the two dosimetry systems are known. The dose unit has changed during implementation because of another standard and another dosimetry protocol. There is a difference between a 2.000 Gy fraction dose in spring 2001 and the same quantity in autumn 2003. The treatments of the patients will be different, although they were planed to be equal. Using the reports of the medical physicists, it is possible to determine the average dose difference for photon and electron beams. Some of the instruments used in both dose determinations performed in the 134 high energy beams of the clinics are the same, like the electrometer, thermometer, barometer and chamber. The uncertainties in the dose ratios for photon and electron beams are estimated to be 1.6 % and 2.2 %, respectively. Trusting the absorbed dose based dosimetry given in TRS 398 [2], we may then express the doses based on air kerma until 2001 as:

For photon beams	+ (1.0 ± 1.6) %
For electron beams	+ (1.5 ± 2.2) %

A more thorough uncertainty estimate will, may be, give lower uncertainties.

In table 1 the uncertainties in a fraction dose are worked out for photon and electron beams for the different standards and protocols. The ratios given above have been employed on a fraction dose of 2.000 Gy, using TRS 398 [2] as the reference. The doses are given together with their uncertainties. For TRS 398 [2] the uncertainties in the protocol are employed, and for the air kerma based dosimetry the values are taken from Andreo P. [22].

When implementing TRS 398 [2] in 2003 in Norway, the table 1 shows the dosimetry situation.

Dosimetry system	**Beam**	**Fraction dose (Gy)**
TRS 398 [2]	Photon	2.000±0,030
TRS 277 [3]	Photon	2.020±0,050
TRS 398 [2]	Electron	2.000±0,042
TRS 381 [4]	Electron	2.030±0,056

Table 1 Doses with uncertainties in one fraction of 2 Gy of dose determination at linac beams using different dosimetry systems.

5.11 Reported experience in USA

The Radiological Physics Center (RPC) in USA has collected experience from 150 institutions from the implementation of the absorbed dose to water standard and protocol, the AAPM TG-51 [23]. Tailor et al. [24] have published the results. The AAPM TG-51 [23] is much the same as TRS 398 [2], and AAPM TG-21 [25] is like TRS 277 [3]. Tailor et al. [24] have the same frequency histograms as, the ones given here in figures 36 and 37. The conclusions are in line with ours, but there seems to be a wider spread in their electron dosimetry. For 18 MV photon beams the institutions reported in average 2 % shift while Tailor et al. [24] have expected 1 %. In our material we do not see this discrepancy between theoretical and reported values. Tailor et al. [24] have long lists of issues causing the deviation between the two protocols. The use of plastic phantoms instead of water phantoms is for them, as for Norway, one of the most important causes for deviations. They also find some confusion in implementing the protocols at the institutions.

6 Medical conclusions

The variability in the clinical situation with regard to treatment intention, tumour radio-sensitivity as well as organs at risk and their radiobiological characteristics, make difficult to arrive to a general conclusion about the consequences of the difference in dose levels by implementation of the TRS 398 as compared with the TRS 277 code of practice.

The intention of radiotherapy may be palliative or curative. According to the WHO, 50 % of all cancer patients will be in need of radiotherapy at one time or other in the course of their disease. Of these, half will need palliative treatment. Patients in need of palliative treatment have a limited life expectancy. This will influence the choice of fraction size, fractionation schedule and the duration of treatment. Thus the dose per fraction is usually larger and the total dose lower as compared to curative treatments, resulting in a shorter overall treatment time.

The palliative effect of radiotherapy is not always mediated through tumour regression. The immediate pain relief sometimes seen after single fraction radiotherapy of bone metastases is probably mediated via effects on the inflammatory process that often attends the metastatic process; inflammatory cells are known to be very radiosensitive. However, little is known about the dose-response relationship of these processes, making it difficult to predict the effects of the dose discrepancies here in question. Palliative treatment has therefore been omitted from the present evaluation.

If the goal of treatment is cure, radiotherapy may be given alone or in combination with other modalities, i.e. surgery or chemotherapy.

In combination with surgery it may be given pre- or postoperatively. The goal of preoperative irradiation is to eradicate microscopic disease which might have spread beyond the margins of the clinical tumour, and to diminish the number of viable cells so that implants in the surgical area are less probable. The goal of postoperative irradiation is to eradicate microscopic disease that might have been left behind after the operation.

For radiotherapy given in combination with chemotherapy, the interaction between radiation and drug is too complex to draw any firm conclusion with regard to the dose discrepancies here in question. In this communication we have therefore concentrated on curative radiotherapy given alone (for local control of gross disease) or with adjuvant intent (for control of microscopic disease).

To evaluate the medical consequences of the present established dose variations, we have to look at the dose response relationship for tumour as well as for normal tissues in question. Radiation dose-response curves have a sigmoid (i.e. S-shape). This holds true for tumour as well as for normal tissue. The dose-response curve is usually characterised by its position and steepness (Bentzen and Tucker [26]). Several descriptors are used for the position of the dose-response curve on the radiation dose scale. They all have the unit of dose (Gy) and they specify the dose required for a given level of tumour control or normal tissue complication. For tumours, the most frequently used position parameter is TCD_{50}, that is the radiation dose for 50% tumour control. For normal tissue reactions, the analogous parameter is the radiation dose for 50% response (ED_{50}) or in the case of severe complications ED_5, that is the dose producing a 5% incidence of complications.

The most convenient way to quantify the steepness of the dose-response curve is by means of the γ-value given by Brahme [27], or the normalised dose-response gradient. This parameter is a dimensionless number that describes how large a change in tumour control probability is to be expected for a given relative decrease in absorbed dose. In fact a dose decrease of one percent on the linear part of the dose response curve will result in a decrease in tumour control probability of precisely γ per cent. Clearly, the value of γ depends on the response level at which it is evaluated. At the bottom or top of the dose-response curve a 1% decrease in the dose will produce a smaller decline in response than that on the steep part of the curve.

There have been numerous publications on the dose response of both human tumours and of normal human tissues. Accurate estimation of the position and steepness of the dose response curve require a large number of mutually dependent dose-response co-ordinates, whose determination is associated with methodological problems of clinical, dosimetrical as well as statistical nature. The most reliable way to establish a dose-response curve is to define γ at the level of response where the curve attains its maximum steepness: at the 37 % or 50 % response level, depending on the statistical model used.

Theoretical and individual dose-response curves are steeper than population based dose-response curves. This is due to inter-patient variability and dose inhomogeneity, alone or together. In general, γ values for human malignancies are subject to error because the patients are usually treated to a relatively narrow range of radiation doses and thus a narrow range of TCP values; very often the data is concentrated in the response range 30-70%. So, even though the steepness at any dose levels in principle can be calculated from γ_{50} and the position of the dose-response curve, we have here chosen γ_{50} because there is very little difference between the statistical dose-response models at this response level.

The γ-value may be used as a multiplier in converting a dose change to a change in response. From data collected from single institutions and from combinations of local control data accumulated from several institutions treating the same disease, Okunieff et al. [28] calculated the γ_{50} for macroscopic and microscopic disease. For macroscopic disease the mean γ_{50} was 3.2 ± 7.6 and for microscopic disease the mean γ_{50} was 2.2 ± 2.9. Thus for an underdosage of 1.0% as revealed by the introduction of TRS 398, a decreased response rate of 3 % and 2 %, for macroscopic and microscopic disease, respectively, is to be expected.

Similarly, the γ-value may be used as a multiplier for converting an uncertainty in dose into an uncertainty in response. As part of a national quality assurance program a dosimetric comparison was carried out by NRPA at all the radiotherapy centres in Norway. Two or more linear accelerators were examined at each centre. The difference of the absorbed dose in photon beams measured by NRPA to that stated by the centre was determined. The mean difference and standard deviation measured at 10 cm depth at the central axis was +1.3 % and ± 1.1 % respectively (see 5.10). This result is clear better than the estimated ±3.3 % by Brahme [27]. Using 1.1 % in his Table 6.1 yields 3 % relative standard deviation in mean absorbed dose to the target. Thus a γ-value of 3.2 and 2.2 would yield an estimated 10 % and 6.5 % standard deviation on the response probability distribution for macroscopic and microscopic disease, respectively. Taking this standard deviation into consideration, a decrease in response rate of 2-3 % will be impossible to show clinically.

Dose-response curves for late normal-tissue end-points tend to be somewhat steeper than dose-response curves for local control of tumours, resulting in a relatively higher response per percent dose decrease. However, the same statistical consideration holds true for normal as for tumour tissue. Since late normal-tissue damage is even more difficult to quantify, the consequences of the present dosimetric discrepancies will also be impossible to show clinically for normal tissues.

In conclusion, the present dose overestimation of 1.0 % will not be clinically detectable.

7 Conclusions and recommendations

The absorbed dose to water calibration in Norway forms the base for dosimetry in high energy radiation therapy. Comparisons of the NRPA calibrations with the Nordic SSDLs and LNHB have showed agreement within the uncertainty. The site visits by the SSDL started a valuable feedback control of the calibration service.

The k_Q used in the clinical photon beams are theoretical and taken from TRS 398 [2]. k_Q determined from LNHB calibrations of NE2611 and NE 2571 chambers deviate at most 0.4 %. The deviation in quality factors, k_Q, from TRS 398 [2] and from a PSDL are small compared with the stated uncertainties.

No dose failure has occurred during the implementation of the absorbed dose to water standard and code of practice. The medical consequences are estimated. Because of the ≈ 1 % lower dose a decrease in response rate may occur, but it will not be clinically detectable. The information about slightly higher dose level before 2001 may be taken into consideration when reworking modalities or evaluating dose escalation studies.

In the Norwegian radiation therapy the dosimetry is harmonized with reference to absorbed dose to water calibration at NRPA and all hospitals use the absorbed to water dosimetry code of practice. The time frame for implementation was from early 2001 to 2003, provided the SSDL has absorbed dose to water calibration in operation. Former dosimetry protocols were not completely implemented in some places. Nonconformities in local dosimetry are reworked and corrections made where needed.

At the dosimetry meeting 5th May 2003 the following recommendations were given:

- Some hospitals use plastic phantoms for routine measurements. It is recommended that handy water phantoms are made available for the absorbed dose determinations for routine use at the clinics.
- For low energy x-rays, the air kerma standard is still used in calibration, and the treatment beams are measured free in air. It is recommended to implement TRS 398 [2] for low energy x-ray beams by measuring on a PMMA phantom.
- A three yearly national dosimetry audit is recommended, and it is strongly advised to take part in the ESTRO EQUAL program.

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