A widely tested model for head scatter influence on photon beam output

Jörgen Olofsson\textsuperscript{a,*}, Dietmar Georg\textsuperscript{b}, Mikael Karlsson\textsuperscript{a}

\textsuperscript{a}Department of Radiation Sciences, Radiation Physics, Umeå University, SE-901 87 Umeå, Sweden
\textsuperscript{b}Division of Medical Radiation Physics, Department of Radiotherapy and Radiobiology, AKH Vienna, Währinger Gürtel 18-20, A–1090 Vienna, Austria

Received 12 February 2002; received in revised form 7 October 2002; accepted 29 December 2002

Abstract

Purpose: To construct and test a semi-analytical model describing the effects on Monitor Unit (MU) verification caused by scattering in the treatment head. The implementation of the model should be accomplished using a small set of experimental data. Furthermore, the model should include a geometry dependent estimation of the resulting uncertainty.

Material and methods: The input required by the created model consists of basic treatment head geometry and 10 measured output factors in air (OF\textsubscript{air}) for square fields. It considers primary energy fluence, scattered radiation from an extra-focal source and from secondary collimators, as well as backscatter to the monitor chamber. Measurements and calculations were performed in open symmetric and asymmetric fields at points located both on and off the collimator axis, as well as at arbitrary treatment distances. The model has been verified for 19 photon beams in the range from 4 up to 50 MV, provided by nine different treatment units from six manufacturers.

Results: The presented model provided results with errors smaller than 1% (2 S.D.) in typical clinical situations for all beams tested. In more exceptional situations, i.e. combinations of unconventional treatment head designs, very elongated fields, and dosimetry points far away from the isocenter, the total uncertainty increased to approximately 2%. The spread in the results was further analysed in order to create a method for predicting the uncertainties under different treatment conditions.

Conclusions: A general head scatter model that is easy to implement has been developed and can be used as the basis for computerised MU verification. The model handles all commercially available treatment units adequately and also includes an estimation of the resulting uncertainty.

© 2002 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Output factor in air; Semi-analytical head scatter model; Extra-focal scatter source

1. Introduction

Quality assurance of monitor unit calculations is an evolving field since technological improvements and developments in radiotherapy offer new possibilities for advanced treatment techniques, e.g. conformal radiotherapy or intensity modulated radiotherapy (IMRT). During the last years methods for monitor unit (MU) calculations and verifications have been subject to recommendations published by the ESTRO and by the Netherlands Commission on Radiation Dosimetry, NCS [6,24]. However, neither of these recommendations cover asymmetric fields, irregular fields shaped by multileaf collimators, nor dynamic and static techniques applied in intensity modulated radiotherapy. In these situations the calculations performed by the local treatment planning system is often relied on as the only source for number of monitor units to be delivered. Since errors in the monitor unit calculation reduce the quality of a treatment, an independent verification of the monitor units is recommended.

The more complex treatment configurations have been addressed in many investigations directly related to head scatter modelling, output factor determination, and monitor unit calculations, respectively [1–3,5,11,15,16,18,21]. The algorithms applied are either based on empirical methods, analytical models, or a combination of both.

During the last years several analytical and semi-analytical models that calculate the relative variation of head scatter or output factor in air with field size have been presented. Many of them are based on two X-ray sources; a primary (focal) source describing the unscattered radiation from the X-ray target, and a distributed (extra-focal) component describing the scatter introduced by the primary collimator, flattening filter, secondary collimators, and backscatter into the monitor chamber. Although it is a common feature in most models that the extra-focal source is directly related to the visible area of the flattening filter, as
seen from the point of interest (‘detector eye view’), different source distributions have been applied. Dunscombe and Nieminen [7] and Jiang et al. [11] assumed a Gaussian distribution, Jursinic [12] used a polynomial term, Sharpe et al. [23] applied a planar extra-focal source, while Hounsfield and Wilkinson [9,10] and Philips et al. [21] used an exponential source distribution. Comparing a triangular, a Gaussian, and a flat source distribution, Ahnesjö concluded that the source distribution itself is not critical [2]. Several attempts have been made to analytically separate the backscatter perturbation from the forward scattered contribution and also to separately describe the scatter coming from the secondary collimators [1,3,11,17,22,27].

The purpose of this paper was to present results on a semi-analytical model for scattering effects in the treatment head. This model has been tested for a large number of open photon beams delivered by accelerators with various treatment head designs. In a first stage and to limit the extent of the current paper, we will present results of open rectangular beams only, i.e. wedged beams and irregular MLC shaped fields will be addressed separately in other communications. The presented model has been developed considering mainly two aspects; firstly, the amount of input data should be limited as far as possible, and secondly, the model should be general enough to accurately describe the head scatter variation in most clinically relevant situations. For exceptional treatment configurations a somewhat poorer accuracy can be accepted. In these cases it is, however, important to keep track of all potential sources of error in order to make a reliable estimation of the resulting uncertainty.

2. Theory

2.1. Basics

The energy fluence coming from the treatment head of a radiotherapy accelerator to a point in air can be separated into a few significant sources. In principle the energy fluence resulting in a monitor signal inside the treatment head, can be assigned to the same few sources. The energy fluence per monitor unit can thus be expressed as:

\[
\frac{\Psi_{\text{tot}}}{\text{MU}_{\text{tot}}} = \frac{\Psi_p + \Psi_e + \Psi_c + \Psi_m}{\text{MU}_p + \text{MU}_e + \text{MU}_c + \text{MU}_m} \tag{1}
\]

where the numerator represents the energy fluence reaching the point of interest and the denominator represents the monitor signal. The indices p, e, c, and m represent primary, extra-focal, collimator, and modulator contributions, respectively (the aspects of introducing a beam modulator is not investigated in this work and will not be mentioned further). This ratio is commonly normalised at a reference geometry, in this study the isocenter point in an open 10 × 10 cm² field, and referred to as the output factor in air (OFair). Unfortunately, \(\Psi_{\text{tot}}\) and \(\text{MU}_{\text{tot}}\) depend quite differently on the field size of the photon beam leading to a non-trivial relation between delivered energy fluence and monitor signal.

2.2. Primary source

In this study the X-ray target was considered to be a geometric point source, which means that the primary contribution \(\Psi_p\) is not affected by the secondary collimators (as long as the point of calculation stays within the field), but is solely dependent on the point of calculation. However, the lateral variation of \(\Psi_p\) itself is a significant effect. These variations have not been studied in detail here, but it is well known that both intensity and beam quality varies in points located off the collimator axis. The explanation for this can be found in interaction processes occurring in the X-ray target and the flattening filter. The primary monitor unit signal \(\text{MU}_p\) is not affected by the secondary collimators since they are not located between the X-ray target and the dose monitor.

2.3. Extra-focal source

Changes in the extra-focal contribution \(\Psi_e\) are generally considered to be the major cause of the field size dependence of \(\text{OF}_{\text{air}}\). Here the extra-focal source represents all forward-scattered photons originating between the X-ray target and the secondary collimators. However, in practice the primary collimator and the flattening filter are the major contributors [1,2,17,26]. In order to get a distribution that mimics the extra-focal photon source well, but also offers a possibility to easily integrate rectangular fields over the source with high accuracy, it is here described as a triangular distribution [2] with a square base, i.e. a pyramid. The base of the pyramid was set to the same area as the circle circumscribing the maximum square field size, at the extra-focal source position \(d_e\). Hence, the side \(e\) of the extra-focal source (Fig. 1) can be calculated according to Eq. (2).

\[
e = \sqrt{\frac{\pi}{2}} \cdot FS_{\text{max}} \cdot \frac{d_e}{d_{\text{iso}}} \tag{2}
\]

where \(FS_{\text{max}}\) is the maximum field size at isocenter. This source has the same orientation as the secondary collimator irrespective of collimator angle.

The reason for the pronounced field size dependence of \(\text{OF}_{\text{air}}\) is that the secondary collimators at some point starts to obscure the extra-focal photon source as seen from the point of interest. The collimator position where this effect arises is described by the relation between the point of interest, the location of the secondary collimators and the position and size of the extra-focal source [11,28]. Instead of projecting every investigated field, i.e. the collimator positions, to the plane of the extra-focal source the source has been projected down to the isocenter plane in a corresponding manner. Fig.
The calculation of \( e_{v} \), corresponding to the upper jaws, is analogous. The benefit of this method is that the field size in the isocenter plane immediately, i.e. without any further calculations, reveals which part of the extra-focal source that is visible from the isocenter point.

However, when the calculation point is located elsewhere a transformation has to be performed. This means that the actual field in the isocenter plane \((X_1, X_2, Y_1, Y_2)\) is converted into a new virtual field \((X_{1v}, X_{2v}, Y_{1v}, Y_{2v})\) that is used for the integration over the extra-focal source. In practice this virtual field shows exactly the same part of the extra-focal source if the calculation point would have been located at the isocenter point instead. The first step for calculation points not located in the isocenter plane, i.e. \( z \neq 0 \), is to use the actual calculation point co-ordinates \((x, y, z)\) to derive four new virtual co-ordinates \((x_{1v}, x_{2v}, y_{1v}, y_{2v})\), each one associated with one of the four secondary collimators. In Fig. 2 it is shown how the virtual co-ordinate named \( x_{1v} \), associated with jaw X1, can be found using Eq. (4).

\[
x_{1v} = \frac{d_i}{d_{iso}} X_1 + \left( x - \frac{d_i}{d_{iso}} X_1 \right) \frac{d_{iso} - d_i}{d_{iso} - d_i - z}
\]  

The calculation is analogous for \( x_{2v}, y_{1v}, \) and \( y_{2v} \). Note that Eq. (4) is only valid if collar X1 is one of the lower secondary collimators. Using the four virtual co-ordinates \((x_{1v}, x_{2v}, y_{1v}, y_{2v})\) the next step is to convert the four actual collimator positions \((X_1, X_2, Y_1, Y_2)\) into the four virtual ones \((X_{1v}, X_{2v}, Y_{1v}, Y_{2v})\) that correspond to the collar setting valid if the calculation point would have coincided with the isocenter point. For the X1-jaw this can be done according to Eq. (5), as illustrated in Fig. 2.

\[
X_{1v} = X_1 - x_{1v} \frac{d_{iso}}{d_i} \frac{d_i - d_e}{d_{iso} - d_e}
\]

If \( x_{1v} = 0 \) then \( X_{1v} = X_1 \), which means that the actual jaw position is used in the integration over the extra-focal source. The calculation is analogous for \( X_{2v}, Y_{1v}, \) and \( Y_{2v} \).

Using this method it is possible to determine the visible area in the plane of the extra-focal source for any rectangular field, symmetric or asymmetric with respect to...
the isocenter. The calculation point may be any point in space downstream from the collimator, i.e. inside or outside the field edge. It is also possible to calculate the visible area for a complex field, e.g. formed by an MLC, by decomposing it into a number of narrow rectangular fields. However, not taking into account the extent of the collimators in the z-direction in the calculations implies that the view from the calculation point towards the extra-focal source is defined by the upper edges of the respective collimator elements. This is a valid assumption when the calculation point is located within the rectangular field. When it is located outside the field this may not be the case, since it is the lower edge of the secondary collimator closest to the point of calculation that will define the view in these cases. Calculations in points obscured by the collimator means also that the issue of collimator transmission should be addressed. However, such geometries have not been considered here.

The next step in calculating $\Psi_e$ is to integrate the field over the extra-focal source. Fig. 3 shows the entire extra-focal source, i.e. the pyramid, and indicates the visible area as striped. For simplicity the virtual collimator positions $X_{1v}, X_{2v}, Y_{1v},$ and $Y_{2v}$ have been normalised to the base of the pyramid, i.e. $e_i$ and $e_u,$ which means that the integration can be performed over a pyramid with a square base area equal to unity. The integration is evaluated separately for each quadrant of the field. In Eq. (6) the integration over the first quadrant, where $X_{1v}/e_i \leq Y_{1v}/e_u$ in this case, is shown.

$$E_{1,1}(X_{1v}, Y_{1v}) = \int_0^{Y_{1v}/e_u} \int_{X_{1v}/e_i}^{X_{1v}/e_i} A(1-2x_v)x_v \, dx_v +$$

$$\int_{X_{1v}/e_i}^{X_{1v}/e_i} A(1-2y_u)y_u \, dy_u =$$

$$A \frac{X_{1v}}{e_i} \left( \frac{Y_{1v}}{e_u} - \frac{Y_{1v}}{e_u} - \frac{X_{1v}^2}{3e_i^2} \right)$$

(6)

In Eq. (7) the four contributions $E_{1,1}, E_{1,2}, E_{2,1},$ and $E_{2,2}$ are then added to get the total extra-focal integral $E.$

$$E(X_{1v}, X_{2v}, Y_{1v}, Y_{2v}) =$$

$$E_{1,1}(X_{1v}, Y_{1v}) + E_{1,2}(X_{1v}, Y_{2v}) + E_{2,1}(X_{2v}, Y_{1v}) +$$

$$E_{2,2}(X_{2v}, Y_{2v})$$

(7)

By using the sign of the virtual collimator positions in the integration this can be done also when the collimator axis is not included in the field. Furthermore, setting the amplitude $A$ to 3 in Eq. (6) means that the total integral $E$ equals unity when all four quadrants of the pyramid are fully visible.

$E$ includes the shielding effect of the extra-focal source but does not take into account the varying source distance when leaving the isocenter point. In these cases an inverse square law correction was applied where the entire extra-focal contribution was assigned to the collimator axis at distance $d_e$ from the target.

The angular dependence of the extra-focal scatter is not included in the integral either. This effect can be quite significant, particularly in high-energy beams. Therefore multiplicative correction factors were applied for the angular dependence on scatter cross-section and energy loss of Compton scattered photons as described by Ahnesjö et al. [2,4]. The angular correction factors, here referred to as $c_{ang}(\hat{\phi}),$ were derived from the nominal beam energy (MV) and an approximate mean scattering angle $\hat{\phi}$ which corresponds to the angle between a ray line ($v_{cent}$) issuing from the X-ray target towards the central point of the visible area of the extra-focal source ($x_c, y_c, d_e$) and a ray line ($v_{calc}$) from this central point to the calculation point ($x, y, z$). Fig. 4 illustrates the definition of $\hat{\phi}$ and Eq. (8) shows how it was calculated.

$$\hat{\phi} = \arccos \left( \frac{|v_{cent}|v_{calc}}{|v_{cent}|v_{calc}} \right) = \arccos$$

$$\left( \frac{x_c(x - x_c) + y_c(y - y_c) + d_e(d_{iso} - d_e - z)}{\sqrt{x_c^2 + y_c^2 + d_e^2} \sqrt{(x - x_c)^2 + (y - y_c)^2 + (d_{iso} - d_e - z)^2}} \right)$$

Hence, the resulting extra-focal contribution $\Psi_e$ was

---

**Fig. 3.** Extra-focal scatter source and coordinate system. The visible area of the pyramid, used to determine the extra-focal scatter contribution, is indicated as striped. Note that the (virtual) collimator positions are normalized to the base of the pyramid.
calculated according to Eq. (9) where effects of varying shielding, distances, and scattering angles are all taken into account.

\[
\Psi_c = k_{\Psi_c} \cdot E \cdot \frac{(d_{iso} - d_c)^2}{x^2 + y^2 + (d_{iso} - d_c - z)^2} \cdot \frac{c_{amp}(\phi)}{c_{amp}(\phi_0)}
\]  

(9)

\(k_{\Psi_c}\) is the amplitude of the fully visible extra-focal source at the isocenter point.

Similar to the primary monitor unit signal \(\text{MU}_p\), the extra-focal monitor unit signal \(\text{MU}_c\) is not affected by the secondary collimators.

2.4. Collimator source

The forward scattered contribution \(\Psi_c\) coming from the secondary collimators was modelled as being proportional to the length of the irradiated collimator edges, projected down to the isocenter plane, and also laterally invariant within the field. This is based on the idea that this source can be described as an isotropic line source in the collimator plane. In most clinical cases, i.e. when the calculation point lies close to the beam centre compared to the distance to the collimators, using this approach means that the lateral variation within the field is very small. Furthermore, this source was positioned at the upper edge of the lower collimator pair \(d_l\), which means that the upper and lower collimator pairs were handled as one single scatter source. The only influence on \(\Psi_c\) from the location of the calculation point in this simplified model is a distance correction when it is not located in the isocenter plane, i.e. \(z \neq 0\). In these cases an inverse square law correction was applied using the distance from the calculation plane to the collimator plane, relative to the reference geometry. In large fields, particularly when the calculation point lies close to the collimator plane, the use of an inverse square law correction can be discussed since the scatter source can hardly be regarded as a point source. However, in most clinical cases this approximation will not affect the results significantly as forward directed collimator scatter is in fact a minor effect [3]. Hence, \(\Psi_c\) was calculated according to Eq. (10), which is valid for any point within the radiation field. \(k_{\Psi_c}\) is a constant describing the energy fluence, relative to \(\Psi_{tot}\) in the reference geometry, reaching the isocenter point from the collimator edges per field perimeter at isocenter level.

\[
\Psi_c = k_{\Psi_c} \cdot 2(X_1 + X_2 + Y_1 + Y_2) \cdot \frac{(d_{iso} - d_l)^2}{(d_{iso} - d_l - z)^2}
\]  

(10)

The part of the monitor signal that comes from the secondary collimators, \(\text{MU}_c\), was calculated as:

\[
\text{MU}_c = k_{\text{MU}_c} \cdot \text{MC}(X_1, X_2, Y_1, Y_2)
\]  

(11)

where \(k_{\text{MU}_c}\) is a constant determined in the implementation of the model for each photon beam and \(\text{MC}(X_1, X_2, Y_1, Y_2)\) describes the treatment head geometry resulting in the monitor signal from backscatter in the secondary collimators. \(\text{MC}(X_1, X_2, Y_1, Y_2)\) is defined as the irradiated area of the upper faces of the collimators, projected down to the isocenter plane, divided by the distance from the corresponding collimator surface back to the monitor chamber.

\[
\text{MC}(X_1, X_2, Y_1, Y_2) = \frac{\sqrt{\frac{\pi}{2}} \cdot \text{FS}_{\text{max}} \cdot (Y_1 + Y_2) \cdot \left(\frac{\sqrt{\frac{\pi}{2}} \cdot \text{FS}_{\text{max}} - Y_1 - Y_2}{d_l - d_{mc}}\right)}{d_u - d_{mc}}
\]  

(12)

Eq. (12) presumes that the Y-jaws are the upper collimator pair. Furthermore, the uncollimated beam is described according to the extra-focal source, i.e. a square of the same size as the circle circumscribing the maximum collimator opening.

Collimator scatter effects in irregular MLC shaped beams can be modelled using the same approach, i.e. forward directed scatter is considered to be proportional to the length
of the irradiated collimator edges and the backscatter being proportional to the irradiated collimator surface facing the monitor chamber. Nevertheless, the respective MLC designs (lower jaw replacement, upper jaw replacement, third level configuration) need to be considered when implementing MLC in the present model.

2.5. Implementation

To describe the head scatter characteristics of a photon beam (not including lateral variations of $\Psi_p$) solely OF$_{air}$ measured at the isocenter point in 10 square symmetric fields were used as measured input data. The square fields all ranged from $4 \times 4$ cm$^2$ up to maximum field size (usually $40 \times 40$ cm$^2$).

The first step in the implementation of the model was to exclude the effect of forward scattered photons coming from the secondary collimators. The constant $k_{C_c}$ was calculated according to Eq. (13) that is based on the findings of Ahnesjö’s investigation [3].

$$k_{C_c} = \frac{-0.002006 \ln(MV) + 0.01098}{4FS_{\text{max}}} \quad (13)$$

MV is the nominal photon energy of the beam and the denominator is the maximum field perimeter (cm) in the isocenter plane. The calculated values of $\Psi_c$ [Eq. (10)] for the 10 square fields used were then subtracted from the measured OF$_{air}$.

The second step was to eliminate the field size dependency due to backscatter from the collimator jaws into the monitor chamber, i.e. MU$_c$, which is the only field size dependent part of MU$_{\text{tot}}$. Fig. 5 shows an example of the inverted result after step 1 plotted against the backscatter parameter MC [Eq. (12)] for square fields that are large enough to view the entire extra-focal source. The beam constant $k_{\text{MU}_c}$ corresponds to the slope of the linear fit. Hence, knowledge about which fields that are large enough to view the entire extra-focal source is essential. This is defined by the size and position of the extra-focal source and the positions of the secondary collimators, which implies that knowledge about the actual treatment head design can be of considerable value. The position of the monitor chamber $d_{mc}$ turned out not to be critical in the calculations, which resulted in the use of a standard position (based on information on different treatment head designs) 4.3 cm downstream from the extra-focal source.

After removing the field size dependency due to $\Psi_c$ and MU$_c$ from the measured OF$_{air}$, the third and last step was to separate $\Psi_p$ and $\Psi_c$ in the remaining ‘reduced OF$_{air}$’. Using these values and the extra-focal integrals $E$ in the 10 square fields, the amplitude $k_{C_e}$ of the extra-focal source was determined through a linear fit, illustrated in figure 6. The slope corresponds to $k_{C_e}$ and the intersection with the y-axis corresponds to the primary contribution $\Psi_p$ at isocenter.

Even though the third step could be the end of the implementation for a particular photon beam, we decided to optimise the position of the extra-focal source, $d_e$, using the 10 square fields. In practice this means that steps 2 and 3 were iterated until the squared difference between the calculated and measured OF$_{air}$ reached a minimum value. The approach to calculate the position of the extra-focal source $d_e$, including the monitor chamber position $d_{mc}$, rather than to use information on the treatment head design means that in the end the only critical geometric information for the implementation of the model is the secondary collimator location $d_u$ and $d_l$.

3. Material and methods

3.1. Accelerators

Measurements and calculations were performed for 19 high-energy photon beams in the range from 4 up to 50 MV, provided by nine different radiotherapy accelerators (eight linear accelerators and a racetrack microtron) from six
manufacturers. The nine accelerators represented all different treatment head designs presently in use. Table 1 summarises information on the accelerators used to test the model.

In those cases where an MLC was involved in creating square or rectangular radiation fields it was in all cases, except on the Elekta Sli Precise accelerator, used in the same way as collimating jaws which means that the calculations can be performed in a similar manner. However, on the Elekta machine the MLC control software closes opposing leaves outside the open portion of the beam (apart from the one to two leaf pairs that are just outside the field edge on each side) [9,20]. Since the MLC is the collimator layer that is located closest to the extra-focal source, the view from the calculation point is defined by the closed leaf pairs rather than the jaw collimator below, even though the jaws define the actual edges of the radiation field in the direction perpendicular to the leaf motion. This was taken into account in the calculations by using the MLC, together with the actual leaf settings, as the only collimator on the Elekta accelerator investigated in the present study.

3.2. Dosimetric equipment

Measurements for the General Electric and the Elekta linacs were performed at the Department of Radiotherapy, AKH Vienna. For these photon beams a cylindrical ionisation chamber (PTW type 31002, volume 0.125 cm$^3$) positioned at 10 cm depth in a polystyrene mini-phantom was used. The mini-phantom had a circular cross-section of 3 cm in diameter.

All other machines are located at the University hospital of Umeå. For these measurements a circular Perspex mini-phantom with a diameter of 4 cm was used in combination with a cylindrical graphite ionisation chamber (volume 0.5 cm$^3$), placed at 10 cm depth. For collimator openings smaller than 5 cm a semiconductor detector (Scanditronix p-type Si-diode) and semi-spherical build-up caps of different materials and water equivalent thicknesses were used [13], all of them large enough to exclude the influence of electron contamination. The build-up cap for 4- and 6-MV photon beams was made of Perspex, the one for 10, 18, and 20 MV of steel, and for 50 MV a lead build-up cap was used. Build-up caps made of non-water equivalent materials have been shown to be suitable for output factor measurements in air in open beams [25]. As the beam quality remains unmodified in open beams, reading-to-dose conversion factors can be neglected.

3.3. Data for implementation of the model

In a first step output factors in air were measured at the isocenter for 10 square symmetric fields (4 × 4, 5 × 5, 7 × 7, 10 × 10, 12 × 12, 15 × 15, 20 × 20, 25 × 25, 30 × 30 cm$^2$, and maximum field size) for each of the 19 photon beams. These square field data, normalised at 10 × 10 cm$^2$, were then used for the implementation, i.e. to determine the model parameters. This was performed through a least square fit between measurements and calculations of $O_{F\text{air}}$ using the software package MATLAB 6.1.

3.4. Data for testing of the model

3.4.1. Symmetric fields

In a second step, $O_{F\text{air}}$ was determined for a series of rectangular symmetric fields with one field dimension varying between 4 cm and maximum while the other was fully opened and vice versa. Additionally, $O_{F\text{air}}$ was measured in each beam for a small number of rectangular symmetric fields with arbitrary field sizes, but a field length shorter than the maximum field size. All rectangular field data were then used to verify the calculations.

3.4.2. Asymmetric fields—point of measurement on beam axis

When using asymmetric beams it is important to make a distinction between the beam axis and the collimator axis. The beam axis is the ray line issuing from the source and passing through the geometrical center of the field, while the collimator axis is the ray line issuing from the source and passing through the isocenter [8].

In order to test the head scatter model for fields asymmetric with respect to the collimator axis measurements were performed in the isocenter plane for 6-, 10-, and 25-MV photon beams provided by the GE Saturne 43 and for 6- and 20-MV provided by the Varian 2300C/D.

On the GE Saturne 43 equipped with an MLC, the leaves in lower position (X-direction) can perform an over-axis travel of 10 cm while the jaws in the upper position (Y-direction) can perform an over-axis travel of 20 cm. For off collimator axis measurements at the University of Vienna, an experimental technique was used where the gantry of the accelerator was tilted while the mini-phantom was maintained vertical. Details on this method can be found in the literature [8]. Measurements were performed on the beam axis of square fields in the range from 4 × 4 to 30 × 30 cm$^2$ for the following beam axis positions in the X-direction (direction of leaf movement): 1.7, 3.5, 5.2, 7, 10.5, 12.3, and 14 cm. This corresponds to gantry angles of 1, 2, 3, 4, 6, 7, and 8°, respectively.

The independent upper jaws (Y-direction) on the Varian 2300C/D can perform an over-axis travel of 10 cm while the independent jaws in the lower position (X-direction) allow an over–axis travel of only 2 cm. On this machine measurements were performed on the beam axis of asymmetric square fields in the range from 4 × 4 to 20 × 20 cm$^2$ for the following beam axis positions: 3, 6, 10, and 12 cm in the Y-direction, and 3, 6, and 8 cm in the X-direction. The measurement technique used was slightly different from the GE measurements: The gantry remained vertical while the detector (Si-diode) and the semi-spherical
Table 1
Specifications of the radiotherapy accelerators considered in this study, including summary of the model parameters for the 19 investigated photon beams

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Linac type</th>
<th>Photon beam energy (MV)</th>
<th>Upper coll. $d_u$ (cm)</th>
<th>Lower coll. $d_l$ (cm)</th>
<th>Extra-focal source $d_e$ (cm)</th>
<th>Primary fluence $\Psi_p$ (at isoc.)</th>
<th>Extra-focal fluence $k_{\psi_e}$</th>
<th>Backscatter constant $k_{\text{MUc}}$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varian</td>
<td>Clinac 2300C/D</td>
<td>6</td>
<td>28.0</td>
<td>36.7</td>
<td>10.4</td>
<td>0.941</td>
<td>0.070</td>
<td>2.08E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>28.0</td>
<td>36.7</td>
<td>10.4</td>
<td>0.948</td>
<td>0.062</td>
<td>2.48E-04</td>
</tr>
<tr>
<td></td>
<td>Clinac 600C</td>
<td>4</td>
<td>28.0</td>
<td>36.7</td>
<td>12.6</td>
<td>0.961</td>
<td>0.053</td>
<td>8.37E-05</td>
</tr>
<tr>
<td></td>
<td>Clinac 4/80a</td>
<td>4</td>
<td>20.3</td>
<td>30.3</td>
<td>11.1</td>
<td>0.940</td>
<td>0.081</td>
<td>2.02E-06</td>
</tr>
<tr>
<td>Scanditronix</td>
<td>MM 50 (MLC)</td>
<td>10</td>
<td>36.3</td>
<td>59.2</td>
<td>15.0</td>
<td>0.937</td>
<td>0.065</td>
<td>2.42E-04</td>
</tr>
<tr>
<td></td>
<td>Race track</td>
<td>20</td>
<td>36.3</td>
<td>59.2</td>
<td>15.4</td>
<td>0.943</td>
<td>0.059</td>
<td>1.90E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>36.3</td>
<td>59.2</td>
<td>18.1</td>
<td>0.947</td>
<td>0.060</td>
<td>1.45E-04</td>
</tr>
<tr>
<td>BBC</td>
<td>Dynaray CH-6</td>
<td>6</td>
<td>38.5</td>
<td>49.5</td>
<td>17.6</td>
<td>0.911</td>
<td>0.105</td>
<td>1.25E-04</td>
</tr>
<tr>
<td>General Electric</td>
<td>Saturne 43</td>
<td>6</td>
<td>24.2</td>
<td>27.9</td>
<td>12.5</td>
<td>0.943</td>
<td>0.105</td>
<td>1.46E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>24.2</td>
<td>27.9</td>
<td>12.7</td>
<td>0.939</td>
<td>0.123</td>
<td>1.72E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>24.2</td>
<td>27.9</td>
<td>12.8</td>
<td>0.940</td>
<td>0.120</td>
<td>1.67E-04</td>
</tr>
<tr>
<td>Saturne 43 (MLC)</td>
<td>6</td>
<td>28.2</td>
<td>35.7</td>
<td>13.5</td>
<td>0.941</td>
<td>0.087</td>
<td>1.68E-04</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>28.2</td>
<td>35.7</td>
<td>13.4</td>
<td>0.931</td>
<td>0.103</td>
<td>1.60E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>28.2</td>
<td>35.7</td>
<td>13.3</td>
<td>0.934</td>
<td>0.098</td>
<td>1.64E-04</td>
</tr>
<tr>
<td>Elekta</td>
<td>SLi Plus (MLC)</td>
<td>6</td>
<td>29.8</td>
<td>43.1$^b$</td>
<td>14.5</td>
<td>0.952</td>
<td>0.073</td>
<td>5.88E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>29.8</td>
<td>43.1$^b$</td>
<td>15.1</td>
<td>0.947</td>
<td>0.084</td>
<td>3.60E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>29.8</td>
<td>43.1$^b$</td>
<td>13.0</td>
<td>0.926</td>
<td>0.099</td>
<td>6.72E-05</td>
</tr>
<tr>
<td>Siemens</td>
<td>Primus (MLC)</td>
<td>6</td>
<td>19.7</td>
<td>28.3</td>
<td>8.7</td>
<td>0.941</td>
<td>0.083</td>
<td>3.80E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>19.7</td>
<td>28.3</td>
<td>8.8</td>
<td>0.943</td>
<td>0.081</td>
<td>2.58E-05</td>
</tr>
</tbody>
</table>

The model parameters given in the last four columns were obtained from a fitting procedure using measured OF$_{\text{air}}$ in 10 square symmetric fields.

$^a$ Source-Isocenter-Distance = 80 cm (the only accelerator in this work where SID is not equal to 100 cm).

$^b$ Only the upper collimator value, i.e. the MLC, is used in the calculations due to the automatic leaf setup together with the treatment head design.
build-up cap, showing practically no angular dependence, was moved laterally in the isocenter plane.

In all points located off the collimator axis the lateral variation of the primary energy fluence $\Psi_p$ was extracted from measurements of OF$_{air}$ at the isocenter level in maximum field size. However, one should keep in mind that these values of $\Psi_p$ are dependent on the measurement depth due to the lateral softening of photon beams. When using them in order to test the model, these effects will cancel out as long as the same dosimetric equipment is used throughout the measurements (under the assumption that the influence from field size on the beam quality is negligible). Furthermore, this means that they should not be used in more general cases, like full dose calculations off the collimator axis.

3.4.3. Asymmetric fields—point of measurement off beam axis

Additionally, measurements were performed off beam axis in a series of asymmetric fields for 6 and 20 MV on the Varian 2300C/D. The measurement point was located 12 or 15 cm away from the collimator axis or on the collimator axis. Collimator positions for the $y = 12$ and 15 cm point of interest were $X1 = X2 = Y1 = 20$ cm while $Y2$ was altered (0, $-5$, $-8$, and $-10$ cm). For the same measurement positions and $Y2$ openings another series was performed for the following collimator settings: $X1 = X2 = 3$ cm while $Y1 = 15$ cm (for $y = 12$ cm) and $Y1 = 18$ cm (for $y = 15$ cm), respectively. For the $x = y = z = 0$ cm position, 12 arbitrary asymmetric collimator settings were investigated.

3.4.4. Arbitrary treatment distances ($z \neq 0$)

In order to test the models ability to calculate OF$_{air}$ at arbitrary treatment distances, measurements were performed at planes located $\pm 20$ cm away from the isocenter plane for 6- and 20-MV beams provided by the Varian 2300C/D. OF$_{air}$ values were calculated and measured at $x = y = 0$ cm and $z = \pm 20$ cm for square symmetric fields of 5, 10, 20, and 40 cm side lengths. For square asymmetric fields of the same size but centred 10 cm off the collimator axis in the $Y$-direction as well as for the maximum field size measurements and calculations were performed at the following co-ordinates: $x = 0$, $y = +12$, $z = -20$ cm and $x = 0$, $y = +8$, $z = +20$ cm, respectively. The measurement technique was the same as for the asymmetric beams on the same accelerator, but the detector and build-up cap were moved perpendicular to the isocenter plane as well.

The variation of the primary energy fluence $\Psi_p$ was in this case measured at the corresponding point at the isocenter plane, i.e. $y = 0$ and $+10$ cm respectively, and then converted to $z = -20$ and $+20$ cm using an inverse square law correction.

3.5. Measurement uncertainties

In all measurements the dose monitoring system of the investigated accelerators was used to determine the output factors in air. Judging from the reproducibility of measurements performed under identical conditions the introduced random errors were in the order of 0.2%. The potentially largest errors in OF$_{air}$ associated with field size, i.e. collimator positioning, occur at small field sizes. The actual field size in our measurements was correct within $\pm 2$ mm at the isocenter level, which implies that even for a $4 \times 4 \times 4$ cm$^2$ field this effect did not result in errors exceeding 0.2%. So, for OF$_{air}$ measured at the isocenter, we estimated the overall uncertainty to be approximately 0.3%.

In measurement points not coinciding with the isocenter, an additional uncertainty is introduced due to small errors when positioning the detector. Assuming that these misalignments were in the order of 1 mm the resulting errors amount to less than 0.1% in the lateral case, based on the maximum gradient of the energy fluence. Parallel to the collimator axis the additional uncertainty, derived from the inverse square law, was 0.2%.

4. Results

4.1. Symmetric fields

The last four columns of Table 1 show the optimised model parameters for the 19 investigated photon beams. Table 2 is a summary of the deviations in the calculation results when compared with the measurements. Table 2 contains the results from all symmetric fields at the isocenter, i.e. the 10 square fields used for the implementation of the model as well as all rectangular fields. It is apparent that the maximum deviation found for each photon beam can be quite accurately predicted by adding two standard deviations to the average deviation. A histogram for the results presented in Table 2 is shown in Fig. 7. In order to analyse the results the symmetric fields were separated into two different categories: fields where the long side of the field is up to three times longer than the short side (denoted short fields) and fields where the long edge is more than three times longer (denoted elongated fields). This separation reveals that the larger deviations mainly belong to the category of elongated fields.

Before considering elongated fields in more detail results from the six photon beams provided by the GE Saturne 43 with jaw collimator, i.e. not the MLC, and the Scanditronix MM50 were removed. The reason for this step was that these two accelerators show, at least for elongated fields, significantly larger deviations than the other accelerators and therefore would dominate the analysis and suppress the results from more conventional treatment head designs. In order to analyse the deviations the remaining elongated fields were subdivided into two new categories: fields where the upper collimator elements define the length of the field and vice versa. In the case of the Elekta linac with MLC only one collimator layer (the MLC) was taken into account.
and consequently these data were also omitted here. Fig. 8 shows a histogram for elongated fields tested on the remaining six accelerators.

4.2. Asymmetric fields

The calculations were performed using the model parameters in Table 1, except for the primary energy fluence $\Psi_p$. No differences were found when comparing the deviations in points located on the beam axis, i.e. in the centre of the beam, and at positions off beam axis. However, when dividing the results from all asymmetric fields into points located at less than 10 cm and 10 cm or more away from the collimator axis some differences can be observed.

Table 2
Average, two standard and maximum deviations between calculated and measured OF$_{air}$ for all symmetric fields tested

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Linac type</th>
<th>Photon beam energy (MV)</th>
<th>Number of fields tested</th>
<th>Average deviation (%)</th>
<th>2 x S.D. (%)</th>
<th>Maximum deviation (%)</th>
<th>Field size, maximum dev. (up x low coll.) (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varian</td>
<td>Clinac 2300C/D</td>
<td>6</td>
<td>37</td>
<td>-0.05</td>
<td>0.50</td>
<td>0.6</td>
<td>40 x 8</td>
</tr>
<tr>
<td></td>
<td>Clinac 600C</td>
<td>4</td>
<td>32</td>
<td>-0.16</td>
<td>0.58</td>
<td>-0.7</td>
<td>10 x 5</td>
</tr>
<tr>
<td></td>
<td>Clinac 4/80</td>
<td>4</td>
<td>33</td>
<td>0.08</td>
<td>0.40</td>
<td>0.6</td>
<td>20 x 10</td>
</tr>
<tr>
<td>Scanditronix</td>
<td>MM 50 (MLC)</td>
<td>10</td>
<td>30</td>
<td>0.13</td>
<td>0.89</td>
<td>1.1</td>
<td>40 x 4</td>
</tr>
<tr>
<td></td>
<td>Race track</td>
<td>20</td>
<td>31</td>
<td>0.13</td>
<td>0.77</td>
<td>0.9</td>
<td>40 x 4</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>30</td>
<td>0.15</td>
<td>1.02</td>
<td>1.2</td>
<td>40 x 5</td>
<td></td>
</tr>
<tr>
<td>BBC</td>
<td>Dynaray CH-6</td>
<td>6</td>
<td>32</td>
<td>-0.06</td>
<td>0.50</td>
<td>-0.5</td>
<td>10 x 20</td>
</tr>
<tr>
<td>General Electric</td>
<td>Saterne 43</td>
<td>6</td>
<td>33</td>
<td>-0.22</td>
<td>1.31</td>
<td>-1.6</td>
<td>8 x 40</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>33</td>
<td>-0.46</td>
<td>1.32</td>
<td>-1.6</td>
<td>40 x 5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>33</td>
<td>-0.47</td>
<td>1.24</td>
<td>-1.5</td>
<td>8 x 40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Saterne 43 (MLC)</td>
<td>6</td>
<td>43</td>
<td>-0.07</td>
<td>0.77</td>
<td>0.9</td>
<td>40 x 12</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>43</td>
<td>-0.11</td>
<td>0.86</td>
<td>-1.0</td>
<td>12 x 30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>43</td>
<td>-0.08</td>
<td>0.77</td>
<td>-0.8</td>
<td>8 x 40</td>
<td></td>
</tr>
<tr>
<td>Elekta</td>
<td>SLi Plus (MLC)</td>
<td>6</td>
<td>43</td>
<td>-0.02</td>
<td>0.55</td>
<td>0.6</td>
<td>40 x 20</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>43</td>
<td>-0.07</td>
<td>0.63</td>
<td>-0.6</td>
<td>10 x 40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>43</td>
<td>-0.16</td>
<td>0.68</td>
<td>-0.8</td>
<td>5 x 40</td>
<td></td>
</tr>
<tr>
<td>Siemens</td>
<td>Primus (MLC)</td>
<td>6</td>
<td>32</td>
<td>-0.05</td>
<td>0.70</td>
<td>0.7</td>
<td>40 x 10</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>32</td>
<td>-0.05</td>
<td>0.53</td>
<td>-0.5</td>
<td>8 x 40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>683</td>
<td>-0.08</td>
<td>0.85</td>
<td>-1.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The last column indicates the fields size for which the maximum deviation was observed.

Fig. 7. Histogram for deviations between calculated and measured OF$_{air}$ for all 683 symmetric fields tested. The symmetric fields are separated into short fields (long side $\leq 3 \times$ short side) and elongated fields (long side $> 3 \times$ short side).
Since the angular distribution of the scattered photons is connected to the photon energy the results were also subdivided into beam energies below and above 10 MV. Fig. 9 presents results of deviations for calculation points located at less than 10 cm from the collimator axis, and Fig. 10 for points located at 10 cm or more away from the collimator axis. From Fig. 9 we conclude that there is no indication of a systematic error. For points located 10 cm or more away from the collimator axis, however, this is no longer the case. As shown in Fig. 10, the lower energies are shifted to the negative side and the higher energies to the positive side. This difference is probably connected to the simple angular correction for extra-focal scatter having more impact on the uncertainties as the scattering angles increase.

4.3. Arbitrary treatment distances ($z \neq 0$)

The results from the 32 measurements and calculations performed at arbitrary treatment distances showed an average deviation of $-0.15\%$, a maximum deviation of $-1.0\%$, while two standard deviations amounted to $0.79\%$. No systematic differences were found when comparing the two photon beam energies, i.e. 6 and 20 MV. However, the error distribution suggests that the model slightly overestimates the output factor in air when getting closer to the source and vice versa.

4.4. Uncertainty estimations for the model

Table 3 summarises the findings of all measurements and calculations performed. The column denoted ‘Additional $s/s_0$’ shows an estimate of the relative size of the additional uncertainty in different geometries as compared to the uncertainty $s_0$ of the 10 square fields used for the implementation. Thus, the total uncertainty when combining the different situations ($s_{tot}$) can be found through a quadratic summation. For example, for a short field ($s/s_0 = 1.0$) where the dosimetry point is located in the isocenter plane but 5 cm from the collimator axis ($s/s_0 = 0.8$) the relative uncertainty, for instance the standard deviation, with respect to the 10 square implementation fields would be close to

$$s_{tot} = \sqrt{1^{2} + 1.0^{2} + 0.8^{2}}s_0 = \sqrt{2.64}s_0 \approx 1.6s_0 \quad (14)$$

It seems like the relative numbers in Table 3 are fairly similar for all individual beams, with the exception of the GE Saturne 43 with jaw collimator and the Scanditronix MM50.

5. Discussion

The uncertainty estimations of the model in Table 3 were not adjusted in accordance with the small measurement uncertainties due to their limited significance. Hence, a minor component of the presented uncertainties is in reality not a consequence of shortcomings in the model, but an effect of experimental limitations. Nevertheless, Table 3 indicates that very elongated fields and/or dosimetry points not located in the isocenter point increase the dosimetric uncertainties somewhat using the presented model. Depending on the available measurements, there is also a possibility to split the uncertainty estimations into even finer steps or to add new categories, such as different photon energies. Another option in order to fine-tune the model even further would be to compensate for actual systematic errors that have been found instead of just increasing the uncertainty.
However, considering the present amount of data we
decided on the existing design of the table.
When looking at the results in Table 2, it is obvious that
the GE Saturne 43 with jaw collimator shows the largest
deviations, both with respect to average and maximum
deviations, even though these problems only seem to be
associated with the category of elongated fields. General
Electric (former CGR) linacs are known to have a unique
collimator geometry. Instead of just using two pairs of thick
jaws each individual jaw is designed in two layers, a thin
one and a thick one [19]. Furthermore, they are interleaved
with each other in such a way that the collimator positions,
du and dl, differ by only 3.7 cm, which is significantly less
than in other collimator types. The head scatter behaviour of
this collimator design in comparison with other designs has
already been described by Kase and Svensson in 1986 [14].
One possible effect is that the thin layer in reality might act
as a semi-transparent collimator when defining the view in
the extra-focal plane as seen from the point of interest. In
such a case it is very difficult to determine the extra-focal
contribution $\Psi_c$ using our model. Furthermore, the fact that
beam shaping is performed by two layers of collimators in
each direction instead of just one suggests that the
contribution from photons scattered forward in the collima-
tors themselves, $\Psi_c$, might be larger than in the normal case.
This theory was also supported by calculations where the
value of $\Psi_c$ was increased, resulting in smaller deviations.

The other accelerator that behaves differently from the
group of more common units is the Scanditronix MM50
(Racetrack). The most striking fact about this treatment
Table 3  
Model uncertainty estimation depending on field shape and location of the dosimetry point

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Number of fields tested</th>
<th>Additional s/s0</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 symmetric square fields used for implementation</td>
<td>190 (=1)</td>
<td></td>
</tr>
<tr>
<td>Field shape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short field</td>
<td>458</td>
<td>1.0</td>
</tr>
<tr>
<td>Elongated field</td>
<td>162</td>
<td>1.8</td>
</tr>
<tr>
<td>Asymmetric field</td>
<td>247</td>
<td>0</td>
</tr>
<tr>
<td>Dosimetry point</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off beam axis</td>
<td>54</td>
<td>0</td>
</tr>
<tr>
<td>0 &lt; Coll. axis distance &lt; 10 cm</td>
<td>178</td>
<td>0.8</td>
</tr>
<tr>
<td>Coll. axis distance ≥ 10 cm</td>
<td>69</td>
<td>1.4</td>
</tr>
<tr>
<td>Arbitrary treatment distance</td>
<td>32</td>
<td>1.4</td>
</tr>
<tr>
<td>(z = ± 20 cm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note that all uncertainties are given with respect to the uncertainty s/s0 obtained for the 10 square symmetric fields used to implement the model.

* Results from GE Saturne 43 with jaw collimator and Scanditronix MM50 are not included.

A treatment head design is the extremely large distance between the upper and lower collimator pairs; 22.9 cm (which is the opposite situation from the GE jaw collimator). Another complicating aspect is the fact that the flattening of the beam mainly is accomplished through scanning of the electron beam before it hits the X-ray target. Exactly how this affects the extra-focal source distribution is difficult to know, but it seems likely that the characteristics are somewhat different from the conventional static beam case. Any further analysis of these two accelerators has not been carried out within this work since there are very few MM50 on the market today and the General Electric accelerators are not in production any more.

In this study we have presented and quantified the deviations occurring when using the suggested model. An analysis of the physical effects behind these deviations might be of interest but it requires either extensive Monte Carlo simulations to cover all the investigated accelerators and beams, and/or cumbersome measurements to extract and verify the individual scatter components in each case.

6. Conclusions

The main objective behind this work was to create a general semi-analytical model for the effects from scatter in the treatment head on output factors in air, which at the same time is easy to implement. The presented model is able to handle all different kinds of radiotherapy accelerators used for photon beam therapy, together with arbitrary points of interest within the radiation field.

The results also show that it is difficult to create a simple model that can provide results with an unaffected level of accuracy also for more extreme treatment set-ups and treatment head designs. However, typical errors in nearly all clinical situations are smaller than 1% and in more exceptional cases smaller than 2%. Together with the presented model we have developed a scheme for how to estimate the varying uncertainties under different irradiation conditions. These error limits should then be used in the validation procedure of the primary MU calculation performed in the clinic.

Acknowledgements

This work was supported in part by the ESQUIRE project within the framework of ESTRO and by grants from the Cancer Research Foundation in northern Sweden. The authors would also like to acknowledge Andree Dutreix and Hans Svensson for their scientific support.

References

[16] Kim S, Liu C, Chen C, Palta JR. Two effective source method for the...


