DOSE MEASUREMENTS IN SMALL FIELDS

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Abstract— A rapidly increasing number of teletherapy treatment modalities, e.g. intensity modulated radiation therapy (IMRT), volumetric arc therapy (VMAT) or stereotactic radiosurgery (SRS), is capable of applying small irradiation fields. Field sizes can be as small as 1 cm x 1 cm or below. The main physical and measurement related effects to consider when performing dose measurements in small fields will be introduced. Subsequently, a detailed description is given on how to decide which detector to choose for the measurements and how to perform the measurement.

Keywords— small field dosimetry, detector choice, practical dosimetry, stereotactic therapy fields

INTRODUCTION

An increasing number of teletherapy treatment techniques make use of small and very small radiation fields, for example, stereotactic radiosurgery (SRS), intensity modulated radiation therapy (IMRT) or volumetric arc therapy (VMAT). Using small radiation fields allows the dose to be placed very precisely in the target volume and at the same time to spare healthy tissue which may be in close vicinity. All in all, there is an increasing demand to characterize small fields in dosimetry.

At the same time, small field dosimetry is more demanding than dosimetry of classical field sizes. New physical aspects, such as the volume averaging effect or the lack of secondary electron equilibrium start to play a non-negligible role and the approximations of classical radiation physics, such as the bragg-gray conditions tend to be valid to a lesser extend compared to larger fields. Precise dosimetry in small fields is still a matter of scientific research; international standards are being developed but not ready yet, e.g. [1].

PHYSICAL AND MEASUREMENT RELATED ASPECTS OF SMALL FIELDS

The volume averaging effect

Any detector will average the dose over its volume. If the dose varies over the volume of the detector, this averaging can yield a different signal compared to the signal an infinitesimally small detector would measure in the center of the area of the large detector. This so called *volume averaging effect*, or short *volume effect* leads to two distinct aspects: (i) the dose in the center of a small field is underestimated – important for output factor[1] measurement and reference dosimetry, and (ii) the penumbra is washed out – important for profile scanning [2]. In general, the volume effect is proportional to the curvature (i.e. second derivative) of the dose profile but *not* to the gradient; this is illustrated in Figure 1, see also [3].

Calculation example: to get a feeling for the volume effect, an ideal circular detector in an ideal circular 2D Gaussian field can be assumed. Then, the average signal over the detector area can be calculated and compared to the value in the center of the Gaussian. For a 20 mm FWHM[2] Gaussian dose profile with a 5 mm diameter detector, the resulting volume correction factor is 1.02. In this example, the detector diameter is four times smaller than the field diameter and this leads to 2 % deviation due to volume averaging. This can be formulated as a rough rule: if the detector width is at least four times smaller than the field width, the volume effect will only be a few percent.

In summary, the volume averaging effect can lead to:

- Dose underestimation when measuring output factors in small fields
- Blurring of the penumbra in profile measurements

The safest way to avoid the volume effect, is to choose a detector which is small enough. Another possibility is to partially correct the volume effect by deconvolution techniques [4–7]. This way the good energy response of an ionization chamber can be preserved and the penumbra still reasonably well characterized.

The volume averaging effect in combination with CAX normalization

As explained in the last section, the volume averaging effect can lead to a reduced signal in the center of a field when there is a non-zero field curvature over the detector volume. In most cases, measured profiles are normalized to their central axis (CAX) value. By doing so, the entire curve is multiplied by one factor, $k_{Vol} > 1$.

[1] Also called *total scattering factor*.
[2] Full Width at Half Maximum

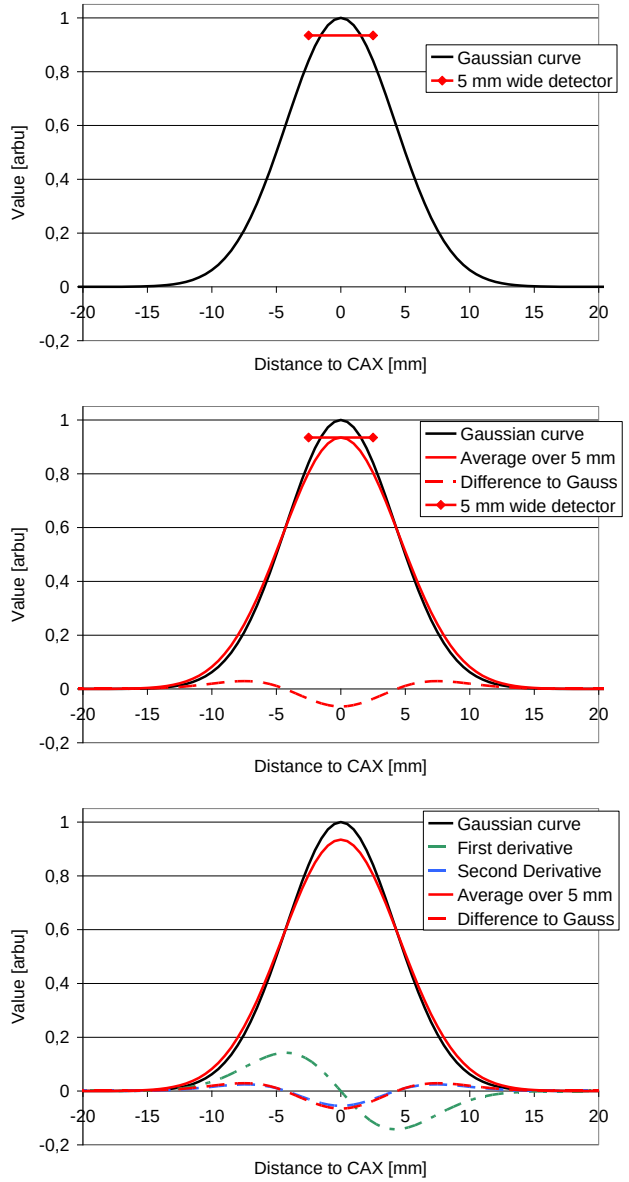

Figure 1. Gaussian curve (solid black) as approximation of a small field profile to illustrate the effects of volume averaging. This is a purely 1D example which leads to the same principle effects but at a different magnitude compared to a full 2D treatment. **Top:** if the size of the detector is larger than the distance in which the field will vary noticeably, a volume averaging effect is expected. **Middle:** the solid red curve represents what a detector would measure when a volume effect is present. The deviation between the two curves in global % is displayed as dashed red line. **Bottom:** in this plot the first (dash-dotted green) and second (dashed blue) derivative of the Gaussian curve are shown. Clearly, the difference curve and the second derivative are proportional to each other. Note, in the high-gradient region at roughly ±4 mm, no volume effect is present – both the difference curve and the second derivative pass through zero.

Since this factor is applied to the entire curve, it also increases the dose in the outer penumbra and out-of-field region. In addition, due to the signal increase in the penumbra, the 50 % isodose moves outwards, i.e. the apparent field size increases. This last effect is only due to the CAX normalization, the original dose measurement exhibits no volume effect at the 50 % isodose because the curvature is zero there, see Figure 1.

In Figure 2, the described effects are presented for a 1 cm x 1 cm field measured with a diamond detector (T60003, PTW-Freiburg, Lörracher Strasse 7, 79115 Freiburg, Germany) and a considerably larger semiflex 0.125 cm³ chamber (T31010, PTW-Freiburg) on an Elekta Synergy SLi18 linac (Elekta, Crawley, UK). Due to the CAX normalization the volume effect in the field center is set to zero but increases outside of the 50 % isodose.

In summary, the volume effect in the field center in combination with CAX normalization can lead to:

- The field appears larger than it is
- The dose outside of the main field is increased in addition to the volume effect alone as described in section 00. See bottom Figure 2.

The low and high energy response

The energy response of any detector should be classified into two parts. (i) The response to photon radiation in the kV energy range and (ii) the response in the MV range. Silicon, for example, exhibits a relatively strong energy dependence in the low-energy range because the ratio of the mass energy absorption coefficients of silicon over water changes considerably in that energy range [8, 9]. On the other hand, Silicon exhibits a relatively low energy dependence in the high-energy range because a slow variation of the mass stopping power ratio of silicon over water in the MeV energy range [9–11]. The kV-energy dependence is especially important when low-energy scattered radiation is present; this is the case in large radiation fields [12, 13].

Hence, for small field dosimetry the kV-energy dependence is of comparatively minor importance. In [14], the use of non-shielded silicon diode detectors is recommended for very small fields.

Signal noise and attainable speed of the measurement

When performing dose measurements, there are several possible sources of noise. The following four are usually the most important ones: (i) quantum noise of the radiation itself, see e.g. [15], (ii) electromagnetic disturbance from the linac environment (iii) noise of the amplifier input of the dosemeter and (iv) noise of the voltage source of the dosemeter.

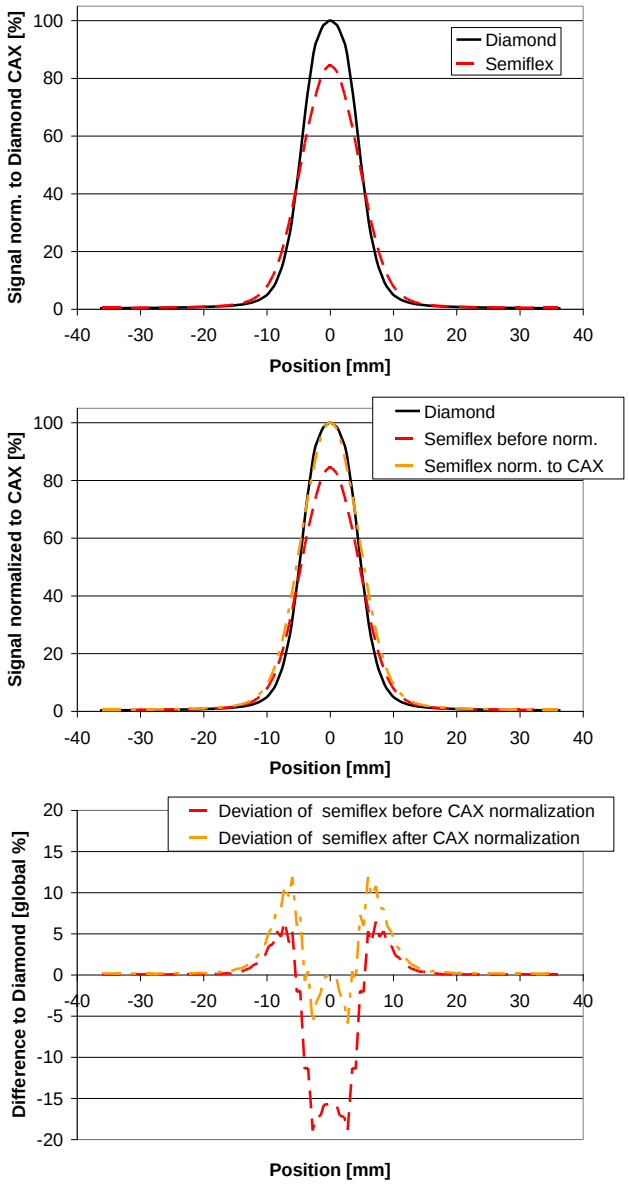

Figure 2. Smoothed profile of a 1 cm x 1 cm field measured with a diamond detector (solid black) and a 0.125 cm³ semiflex chamber (dashed red) on an Elekta Synergy linac. **Top:** both signals have been normalized to the CAX of the diamond detector. The volume effect of the semiflex chamber is clearly visible and leads to a 15.7 % signal loss. **Middle:** each signal has been normalized to its own CAX value, i.e. the entire measurement of the semiflex chamber has been multiplied by 1.19 (dashed orange). Due to this multiplication, the 50 % isodose of the semiflex measurement seems to lie further outward than in the original measurement where both detectors correctly measure the dose at 50 % isodose. In addition, the dose outside of the field is overestimated by the factor of 1.19. This increases the deviation due to the volume effect outside of the main field as can be seen in the **bottom graph**, where the difference between semiflex and diamond curves before and after CAX normalization is displayed in global %.

When using a high-quality dosemeter and detector, the noise from the amplifier, voltage source and electromagnetic disturbance only contribute very little to the cumulative noise. In this case, quantum noise is the most important contribution. Quantum noise measurements have been performed in Co-60 radiation and at a SIEMENS Primus linac (SIEMENS, Erlangen, Germany) [16–18].

At first, one might assume that noise is only a function of the *response* of the detector. But this is not the case. The magnitude of the quantum noise mainly depends on the detector *volume* and *material*. For example, the quantum noise of a PinPoint chamber (type 31014, PTW-Freiburg) is a lot less than the noise of a Diode E (T60017, PTW-Freiburg), even though the response of the diode is 22.5 times higher [18]. If only detectors of the same material are compared, e.g. only diamonds or only air-filled ionization chambers, quantum noise usually reduces with increasing volume and response [18].

Quantum noise follows Poissonian statistics. Hence, in contrast to many other sources of noise, quantum noise is a function of the signal [18, 19]:

$$\text{Quantum noise} = \sqrt{\text{Signal}} \tag{4}$$

When measuring relative data, e.g. profiles or output factors, the signal and hence also the noise are normalized to the signal itself. This yields the relative quantum noise:

$$\text{Relative quantum noise} = \frac{1}{\sqrt{\text{Signal}}} \tag{5}$$

Hence, the lower the signal, the higher the relative noise. The extent of noise in the signal plays a role in the attainable speed of the measurement. The lower the noise, the faster the signals can be recorded. Ionization chambers typically exhibit less quantum noise than diodes.

Depending on the quality of the dosemeter, amplifier and voltage source noise may add to the quantum noise. In that case an ionization chamber measurement might exhibit more noise than necessary.

Detector positioning in the field center

Small fields typically show no plateau in the field center. Hence exact detector positioning in the center of the field is a lot more important than in dosimetry of larger fields. The detector should be aligned to the field center by measuring profiles in shallow and large depths [14].

Using a reference detector

When measuring profiles, PDD curves, or TPR data, it is common practice to place a reference detector in the corner of the radiation field to correct for fluctuations of the linac output. In small fields there is not enough space to place such a reference detector inside the field. One possible

solution for this problem is to use the linac monitor chamber as a reference detector. Unfortunately this signal is usually not accessible. Alternatively, the measurement can be performed without reference detector or by use of a very high response detector which is placed outside of the field [14]. When measuring without reference detector, it has to be assured that the output of the linac is stable in time, e.g. by measuring the profile multiple times. In this case, the linac fluctuations will be source of noise. A high quality but slow alternative is measuring step by step, irradiating a fixed number of MUs at each detector position.

Using a reference detector outside the field: The dose rate outside the primary beam is usually very low, typically a few percent of the primary signal. As described in section 0.0 the relative noise of weak signals will be a lot higher than in the field. Since the result of the measurement is the field signal divided by the reference signal, this will increase the noise of the measurement. To prevent this, a reference detector with a very low quantum noise should be chosen, e.g. a large ionization chamber. The effect is shown in Figure 3, where the signal of a 0.125 cm³ chamber (type 31010, PTW-Freiburg) is displayed, placing the reference detector inside and outside a 4 cm x 4 cm irradiation field of a Varian Clinac iX (Varian Associates, Palo Alto, CA). Clearly, the signal quality is greatly reduced when simply placing the reference detector outside of the field. The situation improves when using the 22.5 times larger Farmer chamber (type 30013, PTW-Freiburg) but the noise still increases. Using the standard deviation as a noise measure and equation (2), the expected noise can be calculated as a function of the signal. For the data in Figure 3, the signal – and hence the volume – of the reference detector has to be increased by a factor of four to reach the noise level of the semiflex chamber in the field. The calculated standard deviations are presented in

Table 2. This is only one single example. The calculated minimum volume depends on the field size and distance from the field edge. A larger chamber is needed when the field size is smaller or when the distance to the beam edge is increased.

Table 2 Standard deviation, as a measure of noise of the signals shown in Figure 3. "Ouside" signifies 3 cm outside of the beam edge as defined by the light field.

Chamber type	**Volume [cm³]**	**In the field or outside?**	**Noise (= standard deviation) [%]**
PTW 31010	0.125	Inside	0,12
PTW 31010	0.125	Outside	0,62
PTW 30013	0.6	Outside	0,29
Hypothetical	2.4	Outside	0,15

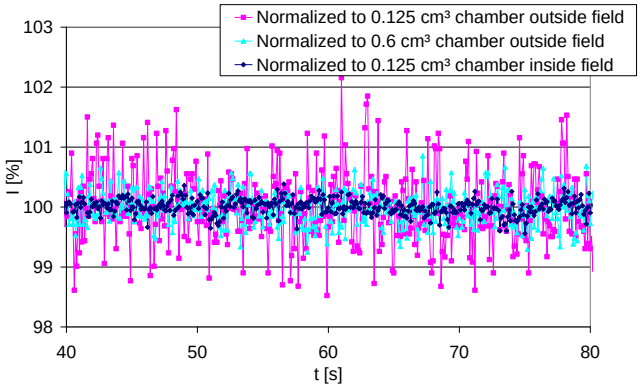

Figure 3. Signal of a 0.125 cm³ chamber in a 4x4 cm² field at roughly 1.5 Gy/min, at 10 cm depth in water. The integration time for each data point is 100 ms. For this measurement, a 0.125 cm³ reference detector has been placed inside the field (blue diamonds) and 3 cm outside the field (magenta squares). For comparison, the result when referencing to a 0.6 cm³ Farmer chamber, located outside the field, is also displayed (cyan triangles).

In summary, the possible options are:

- Using the monitor chamber of the linac
- Ensuring that the linac is stable and measuring without reference
- Using a reference chamber outside of the beam but with a volume well larger than 2.4 cm³. It should be placed as close as possible to the beam edge. The chamber should be pre-irradiated before use outside of the beam.
- Irradiating a fixed number of MUs at each detector position

Dose rate dependence

Some detectors exhibit a dose rate dependence, i.e. the response of the detector can change when the dose rate changes. Depending on the detector in question, this may be a reaction to the changing linac frequency, average dose rate, or dose per pulse. In this article, *dose rate dependence* will be used as general term to describe all three aspects. For air-filled ionization chambers the effects are well understood and can easily be corrected. Nonetheless this correction can be quite time-consuming and for many small field detectors, data on their dose rate dependence is sparse. It is worthwhile to address the question on how much effect a dose rate dependence actually has on the results. When performing reference dosimetry, the dose rate dependence is usually corrected. Hence we are left with its effect on relative measurements only; for example output factors, profiles or PDDs.

Mathematically, the following three operations are done when performing a relative dose measurement:

1. A quantity proportional to dose is measured while changing one parameter of the setup. This parameter can be depth, distance from the CAX, field size or some other parameter.

2. The entire measurement is normalized to one data point of the same measurement, e.g. the value on the CAX. In practice this means, the entire curve is multiplied with one numerical factor.
3. The entire measured curve is displayed as relative values, either in % or as factor where 1 is the normalization value.

In fact, the second and third step is equivalent to calibrating the detector to the conditions valid at the normalization point. After normalization, by definition, the value at this position is exact. Hence, in the flat field part, the profile is in very good approximation not influenced by a dose rate dependence. The more the actual signal deviates from the signal at the normalization point, the stronger can the influence of a dose rate dependence be. At the same time, the absolute deviation is also small at low signals because the signal itself is low. All in all, after the signal is normalized at 100 %, a deviation due to dose rate dependence is best visible at the 50 % dose level. This is illustrated for an idealized profile in Figure 4. The only physical assumptions that are needed for the data are that the dose rate dependence is linear with the dose per pulse and that the saturation loss is maximal at the highest dose per pulse. These assumptions are reasonable for ionization chambers [20].

As explained above, the error vanishes at the normalization point on the CAX. This is clearly visible in the bottom part of Figure 4. In the low dose region the error tends to very small values because we look at global % values. These are small when the signal is small. The highest deviation of the normalized curve is in the penumbra because the signal is relatively far away from the normalization value but still high enough to yield an observable global % difference value.

In summary, the normalization procedure leads to:

- The maximum deviation in global % is only 1/4th of the saturation loss at the normalization point
- This maximum deviation is located in the penumbra
- The deviation changes sign

The same estimation can be performed for PDD curves, where the maximum deviation is also 1/4th and located at the 50 % dose value of the curve.

Similar considerations hold for the measurement of output factors. In most cases, the signal range without changing the detector will be roughly 70 to 120 % of the signal at the normalization point. The maximum deviation is hence a bit less than the 1/4th of the maximum signal deviation encountered in profile and PDD measurements.

Ionization chambers and diamond detectors tend to exhibit a loss of response at high dose rates while for diodes the opposite behavior is possible [21].

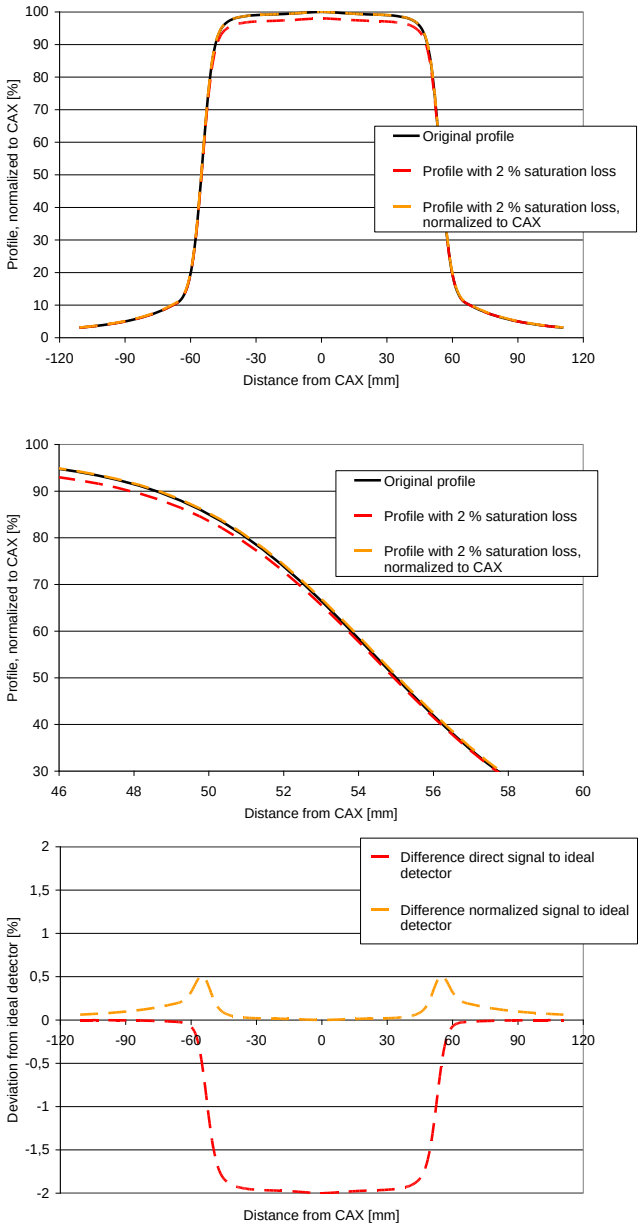

Figure 4. Theoretical profile of a 11 cm x 11 cm field measured by an ideal detector (solid black), a detector exhibiting a dose rate dependent saturation loss of up to 2 % (dashed red) and of the signal normalized to the CAX value (dashed orange). **Top:** full profile, **middle:** zoom into the upper right part of the profile and **bottom:** difference in global % between the curves.

Non-linear relation between field size defined by the collimators and field size defined as 50 % isodose

In large fields, there is a one to one correspondence between the field size set by the collimators and the actual field size. In small fields, the focus can be partly obscured by the collimator blocks. This leads to the field size – as defined by the 50 % isodose – to reduce faster than the

collimator opening. Hence the relation between field size set on the collimators and the actual field size can become non-linear for very small fields [22].

In the case of source occlusion, the actual shape of the field may depend on the size and shape of the focal spot. The shape of the focal spot might vary in time or if a different linac model of the same type is used. In these cases, the field shape will also vary. [22]

Lack of secondary electron equilibrium

As soon as the distance to the closest field edge is smaller than the travel distance of scattered secondary electrons, equilibrium of secondary electrons breaks down. As a rough estimation the range of laterally scattered secondary electrons is similar to the depth of the dose maximum of a PDD in 10 cm x 10 cm. Precise data is given in [23]. Some of the assumptions of classical dosimetry break down when lateral electron equilibrium is not given. The electron energy distribution over the volume of an air-filled ionization chamber is, for example, not constant in contrast to equilibrium conditions. The consequences of lack of secondary electron equilibrium are still in scientific discussion, see e.g. [14].

Correction factors from literature

Recently, many articles have been published providing correction factors for certain detectors, e.g. [1, 3, 24–27]. When using these factors, care has to be taken to adapt them to the dosimetry protocol employed because the precise value of these factors may depend on the specific protocol used. For example, the value of the beam quality correction factor k_Q is different in TRS 398 [28] and DIN 6800-2 [29], and TG-51 [30] uses a different measure for the radiation quality. k_{Vol} may depend on the specific linac model in question as the precise shape of the beam depends on the size of the focal spot of the electrons on the target [14, 22].

Other aspects

High density detectors: many small field detectors are solid state detectors, e.g. silicon diodes or diamond detectors. These are high density materials, of 2.3 and 3.5 g/cm³ density, respectively [3, 26]. Recently, some publications claim an influence of the density of the detector material on the measurement in small fields [26, 31].

Cable and stem effects: due to the very small volume of microchambers of less than 0.1 cm³, stem and cable irradiation effects are a lot stronger than for standard ionization chambers. To be on the safe side it is reasonable to perform a polarity correction. To reduce the influence of the cable, it can be mounted in a way that the irradiated cable length changes as little as possible during the measurement. For example, the chamber can be mounted in axial orientation – this will, by the way, also increase the spatial resolution in most cases. When purchasing such a chamber it is important to watch for the water equivalence, e.g. a steel electrode is not preferable [14].

FFF beams: often, therapy systems using small fields are flattening filter free (FFF) linacs. The field is then never flat in the field center, even for large fields. A Farmer chamber might already show a volume effect in any field size [32]. In addition, the dose per pulse values and dose rate can be elevated for FFF linacs.

Penumbra more important: in general, when working with small fields, it is more important to precisely characterize the penumbra and out-of-field region. When many small fields are added up, a comparatively large fraction of the dose stems from the penumbra, and for field sizes roughly below 3 cm x 3 cm, the field consists almost only of penumbra [22]. The penumbra width, e.g. the spatial distance between 80 and 20 % dose, is smaller in small fields. This increases the curvature and hence the volume effect in the penumbra region.

Electron and photon spectrum can change with field size: in small fields, the energy spectrum of the primary photons and secondary electrons can change with the field size. For some examples see [14].

Divergence of the beam: divergence of the beam can, via the volume effect, lead to a slight overestimation of 1 % in a PDD measurement deep in the water [26]. Because of the small opening angle of small field beams, this effect is relatively weak.

HOW TO CHOOSE THE DETECTOR

Choosing the correct detector for small field measurements is not an easy task. There are no simple rules or standard detectors. Some insight into the physics of small fields is needed, and it has to be considered what exactly should be measured. Then a compromise between all requirements has to be found. The following chapter shall give a guideline for the decision process.

Detector types

In large fields, air-filled ionization chambers are usually the first choice. In small field dosimetry different types of detectors are in use.

Medium-sized vented air-filled ionization chambers show a very good water equivalence in the kV energy range. The MV energy dependence can be corrected by applying k_Q values from literature. Their volume is in the order of 0.1 to 1.0 cm³. The only disadvantage of these chambers is their relatively large volume which can lead to a volume effect. Depending on the model in question, these chambers can be used down to field sizes of 3x3 cm² [33].

Small-size vented air-filled ionization chambers, sometimes referred to as *microchambers* or *pinpoint*

chambers, show a good water equivalence in the kV energy range and their MV energy dependence can also be corrected using k_Q values from literature or from the manufacturer. Due to the very small volume of less than 0.1 cm³ of these chambers, stem and cable effects, e.g. the polarity effect, become more important than for larger ionization chambers, especially when used in a wide range of field sizes. When used in axial orientation, i.e. the chamber axis facing in the direction of the focus, the spatial resolution of these chamber can be as good as 2 mm [33]. Be careful not to use a microchamber employing a steel electrode, this will lead to a stronger energy dependence [14].

Silicon diodes are solid state detectors and currently the smallest detectors available on the market. They are usually not subject to the volume effect except in extremely small fields [26, 31, 34]. Usually, silicon detectors exhibit a directional dependence and a strong energy dependence for kV energy photons. When used in small fields, the kV energy response is of minor importance, hence unshielded silicon diodes can be used in small field dosimetry and are often the detector of choice [14]. The MV energy dependence is better than for air but still non-zero. To measure reference doses, the detector needs to be cross calibrated in conditions as close as possible to the envisaged operating conditions, e.g. in a 4 cm x 4 cm field at the same radiation quality.

Diamond detectors are a very advantageous combination of the required properties of a small field detector. Diamond basically has no MV energy dependence – the ratio of the mass stopping power of carbon to water is constant in the MeV range [10] – and the kV energy response is very good. In addition, the angular response is very homogeneous. Diamonds may exhibit a weak dose rate dependence [35], which can be corrected.

Plastic scintillation detectors read out a relatively weak optical signal, hence they tend to exhibit a very strong noise [36, 37] and need very long integration times. In addition, the temperature dependence is quite high [38]. It is challenging to control the Cherenkov part of the signal in the light guide which can lead to relatively strong cable irradiation effects [39].

Detector selection criteria

To choose a suitable detector, it is first of all necessary to determine the basic requirements. These are:

- What is the minimum field size required?
- What is the maximum field size required?
- What has to be measured?
  - → Output factors or reference doses according to a dosimetry protocol
  - → Relative doses (profiles and PDDs)
- Is it an option to use more than one detector?

Once decided upon the requirements, these can be cross-checked against the technical data of the detectors to see which detectors are the most suitable. Usually, a choice of more than one detectors is possible. Then, the following criteria can help to decide which detector to take in the end. Often, the best results can be obtained using a combination of two or more detectors.

Reference dosimetry: if the task is to measure absolute doses using reference dosimetry, then a calibrated detector is needed as well as a dosimetry protocol, publication or manufacturer specification providing correction factors. To date, this is only possible for air-filled ionization chambers.

Penumbra precision: the smaller the detector, the more accurate is the characterization of the penumbra.

Out-of-field dose precision: outside of the field, the kV fraction of the radiation is strongly increased. If a precise measurement of dose outside of the field is desired, a detector featuring a low kV energy dependence should be chosen. In case this is a relatively large chamber, a volume effect in the field center in combination with CAX normalization can lead to an overestimated out-of-field and outer penumbra dose – independent of the kV response.

Dose stability: diodes reduce their response with accumulated dose. For profile, PDD and TPR measurements, this is usually not a problem, the diode must only be stable during each scan. To measure output factors, it must be ensured that the diode is cross calibrated often enough. Air-filled ionization chambers and diamond detectors are in general very stable with accumulated dose.

Dose rate independence: most detectors, will show a slight dose rate dependence. For relative dose measurements, this usually only leads to a small uncertainty as shown in section 0, but it should be considered before performing the measurement. For air-filled ionization chambers, the dose per pulse dependence can be calculated and corrected [20, 28–30].

MV energy response: In very small fields, the energy spectrum of the secondary electrons slightly changes with field size [14]. To be safe from this effect it is good to choose a detector with a low MV energy dependence.

kV energy response: If the fraction of kV radiation in the photon spectrum is expected to vary during a measurement, a detector featuring a low kV energy dependence should be chosen. This is, e.g., the case when measuring in large and small fields with the same detector (output factors) or when high precision is required for in-field dose as well as out-of-field dose (profiles). If the deconvolution technique is used, an ionization chamber might be a good option.

Speed of measurement: As described above, when using high quality equipment, quantum noise will most probably be the main source of noise in the measurement. Choosing a detector with a low quantum noise can save measurement time. Very low quantum noise can be expected from ionization chambers, medium noise from

high-response diodes (roughly above 100 nC/Gy), relatively high quantum noise from low response diodes (roughly below 100 nC/Gy) and highest quantum noise from scintillation detectors [18, 36, 37].

Other aspects to consider

Quality of the dosemeter: the measuring equipment does not only consist of the detector. In addition, a water phantom and a dosemeter are required. If the response of the detector is low, a very high quality dosemeter is mandatory. It is worthwhile to have a close look at signal noise and zero drift of the dosemeter at the lower bound of the current or charge measurement range. The quality of a dosemeter can be checked by applying a precisely defined current or charge to the input [40].

Quality of the water scanning system: due to the high gradients encountered in small field dosimetry, the requirements on accuracy and precision of the position of the water phantom are higher compared to large field measurements.

HOW TO PERFORM THE MEASUREMENT

Reference dose and output factor measurement

By „*reference dose*" this article refers to measuring dose using a calibrated detector in the center of a radiation field [9]. Sometimes, this is also referred to as *absolute dose measurement*. The best way to measure reference dose depends on the field size. If the field size is large enough to allow the use of an air-filled ionization chamber the direct application of one of the international dosimetry protocols, e.g. [28–30], is the best approach. If correction factors of the chamber are not contained in the dosimetry protocol, the information can often be obtained from the manufacturer or from publications.

For field sizes ≥ 4 cm x 4 cm: a medium sized air-filled ionization chamber can be used, e.g. a 0.125 cm³ semiflex chamber. The dose can be directly measured according to a dosimetry protocol.

For field sizes of 2 cm x 2 cm to 4 cm x 4 cm: either a microchamber can be used, following one of the dosimetry protocols, or a small field detector can be cross calibrated against a medium sized air-filled ionization chamber in a relatively small field of 4 cm x 4 cm to 5 cm x 5 cm.

For field sizes below 2 cm x 2 cm: for very small fields a detector that is small enough to exclude the volume effect has to be selected. This detector should be cross-calibrated against a medium sized air-filled ionization chamber in a relatively small field of 4 cm x 4 cm to 5 cm x 5 cm.

Output factors: to measure output factors, all correction factors that neither depend on dose rate or field size can be neglected because it is a relative dose measurement. Other corrections, such as polarity, volume effect, or dose per pulse can be applied to increase the accuracy of the measurement. Before deciding for which field sizes to take which detector, the kV energy dependence of each detector should be considered.

How to perform the cross-calibration:

The cross-calibration is done in a phantom for each radiation quality. It should be performed in two steps in a field of 4 cm x 4 cm or 5 cm x 5 cm:

1. Use a medium-size vented ionization chamber, e.g. a semiflex 0.125 cm³ chamber, to determine the dose D_{ref} for the radiation quality and depth of interest. Use one of the international or national dosimetry protocols, e.g. [28–30].
2. Replace the medium-size ionization chamber by the small-size detector to be cross-calibrated. Make sure the effective points of measurement are located at the same depth. The orientation of the small field detector should be the same as in the consecutive use. Apply the same number of monitor units as before and determine the reading D_{small} of the small-size detector. The cross-calibration factor for the small-size detector is the ratio D_{ref}/D_{small}.

After cross-calibration, the small-size detector can be used in fields smaller than the cross-calibration field and at different depths, but always at the same radiation quality and detector orientation.

Relative dose measurement

When performing relative dose measurements, several details have to be considered.

The detector should be well centered in the field. Since small fields often do not have a dose plateau in their center, detector positioning needs to be done with great care. The positioning should be checked by measuring profiles in shallow and also in large depths. Otherwise the detector might "walk out of the beam" when moved downwards in the water.

The volume effect should be excluded. The detector has to be small enough to exclude the volume effect. This is especially important when measuring output factors where the volume effect can lead to a serious underestimation of the dose value [14]. A volume effect in the field center can lead to overestimation of the field size and out-of-field dose as explained in section 0. A volume effect in the penumbra can partly be corrected by deconvolution.

The integration time should be chosen sufficiently long. Small field detectors often exhibit a higher level of quantum noise than ionization chambers used for larger fields. The integration time per data point has to be chosen long enough to keep the noise in a reasonable limit. To reduce noise by half, the integration time has to be increased

by a factor of four [19]. Some water scanning systems may automatically smooth the signals. To tell how much noise is on the signal, this smoothing must be turned off.

The use of the reference detector has to be considered. Either the reference detector has to be placed outside the field or the measurement has to be performed without reference detector. For the first option, a large chamber must be used or very long integration times chosen, otherwise the noise of the signal will strongly increase. When measuring without reference it must be assured that the linac output is stable in time.

Other details to consider

Concerning the spatial resolution of the measurement, film would be a good choice as relative small field detector. When considering the use of film, it must be kept in mind that the energy response and dose range of radiographic films is not very good and the result depends on the development of the film. Radiochromic films have a very good energy response but need a relatively high dose to develop. In addition, the response of radiochromic films can vary by a few per cent over the area of the film and there are batch to batch variations. Note also, the results of film dosimetry are always somewhat handling dependent [14].

Most examples and figures in this article refer to square fields. If the field is circular, the field edge of the square field can approximately be replaced by the field diameter of the circular field.

If the field is rectangular, the short field edge is more important than the long field edge.

When working with a FFF linac, the field is never flat in the center and the dose per pulse values are elevated.

SUMMARY

Dosimetry in small fields poses new challenges for medical physicists. Positional accuracy is very important, the volume effect should be excluded as much as possible and some of the common measurement methods, e.g., where to put the reference detector in scanning measurements, have to be reconsidered. Reference dose and output factors can be measured by cross calibration in field sizes in the order of 4 cm x 4 cm to 5 cm x 5 cm.

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CONFLICT OF INTEREST STATEMENT

The Author is employee of PTW-Freiburg.

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