Influence of the design of applicators to the dose distribution and therapy concepts in superficial and orthovolt therapy with X-rays

content

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Introduction

In the more than 125 years of therapeutic use of X-rays [3], applicators with a fixed focus-to-skin distance (FSD) and a fixed field size have prevailed over collimators with free collimation and freely selectable FSD.
This applies to all energy ranges of conventional X-ray therapy

- Grenz Ray Treatment (GRT) (5–20 kV)
- Soft and Superficial X-Rays (SXR) (>20–100 kV)
- Deep X-Rays (DXR) (>100–300 kV) (orthovolt x-rays)

The specified field sizes and the fixed FSD guarantee high reproducibility. The complex effects and interactions of the X-ray spectra used can be represented very well in applicator-related dosimetry.

Physical Effects of x-rays

X-rays in the energy range from 10 to 300 keV is characterized by a series of interactions that are countered by the design of applicators in order to enable reproducible therapeutic use while excluding or reducing undesirable side effects.

1. Backscatter depending on the field size

The beam quality and penetrating ability of a x-ray spectrum is significantly mapped with the value of the half-value layer thickness (HVL) [1].
Depending on the HVL, there are dosimetrically and therapeutically relevant backscatter effects of up to 50% [6], [10].

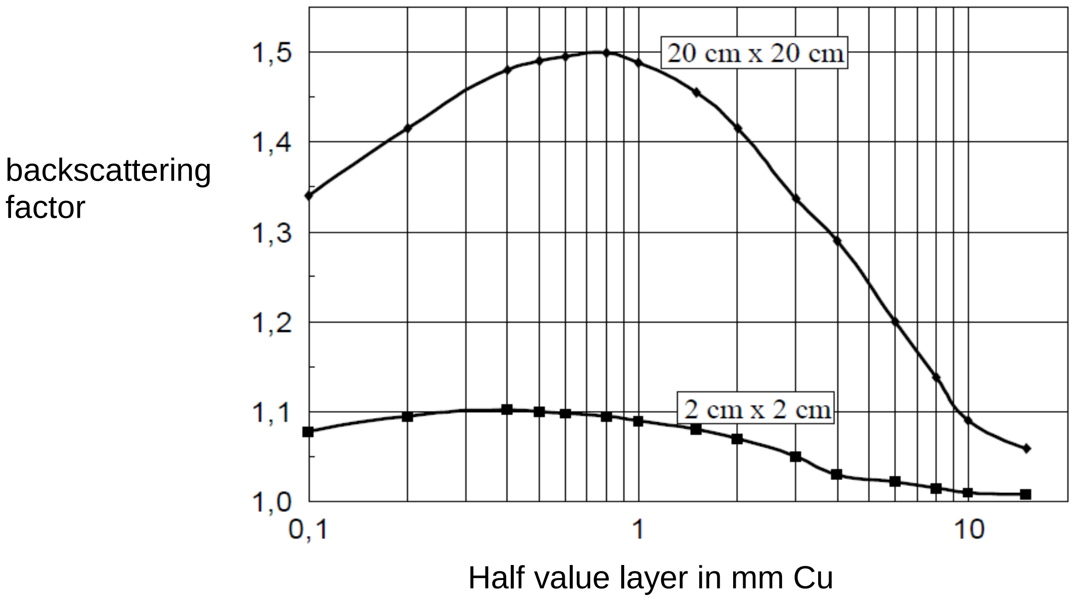


fig. 1.1. of [6]
shows the influence of the field size to the backscatter. The effect is clearest in the range around 1 mm Cu HVL.
0.1 mm Cu HVL correspond ca. 80 kV
1.0 mm Cu HVL correspond ca. 150 kV

In the spectral range of x-ray therapy, backscatter becomes a significant factor in the percentage depth dose.

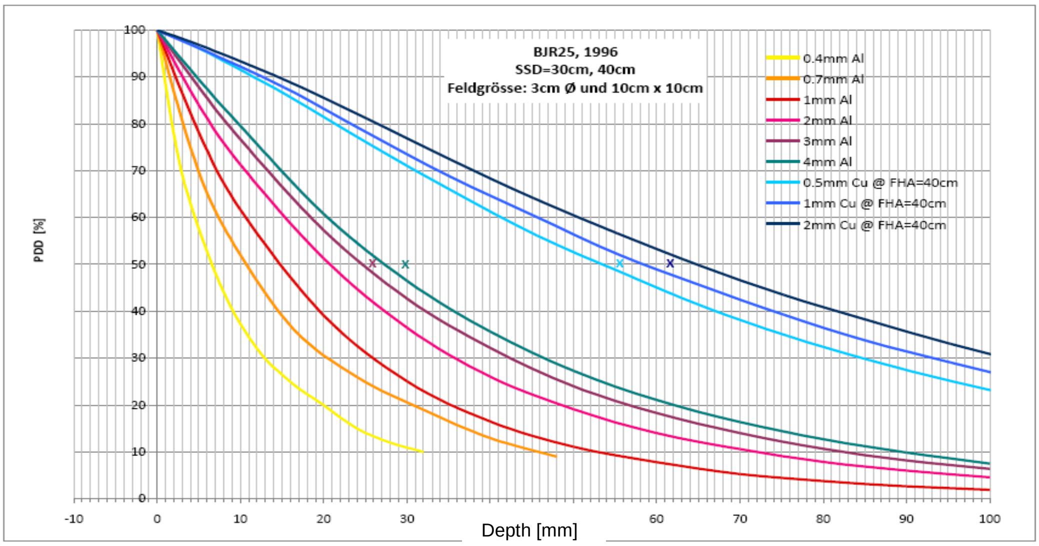


fig. 1.2. of [1]
percentage depth dose as a function of the HVL for FSD 40 cm

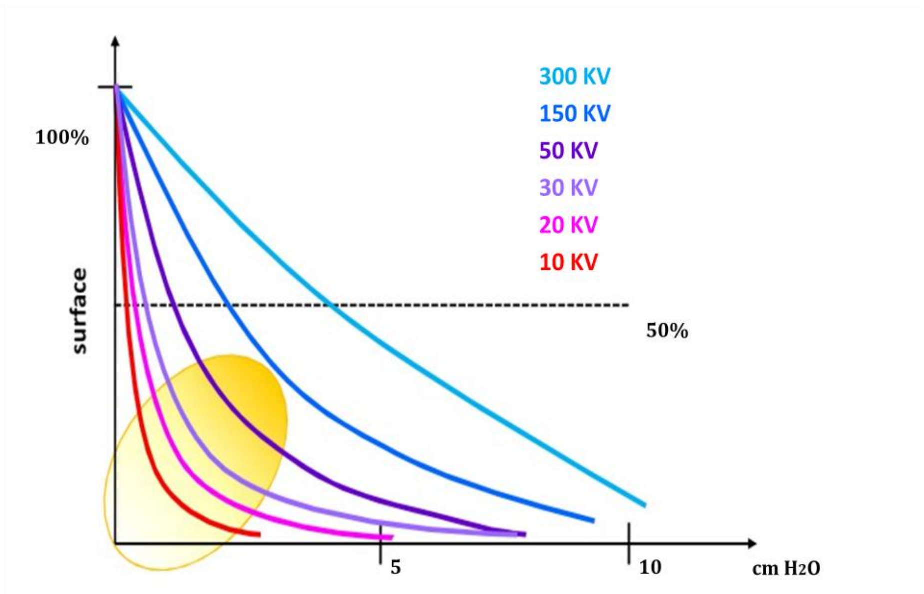


fig. 1.3.
Relationship between tube voltage and (implied) HVL and relative depth dose

The divergence of the beam angle has a further influence on the percentage depth dose

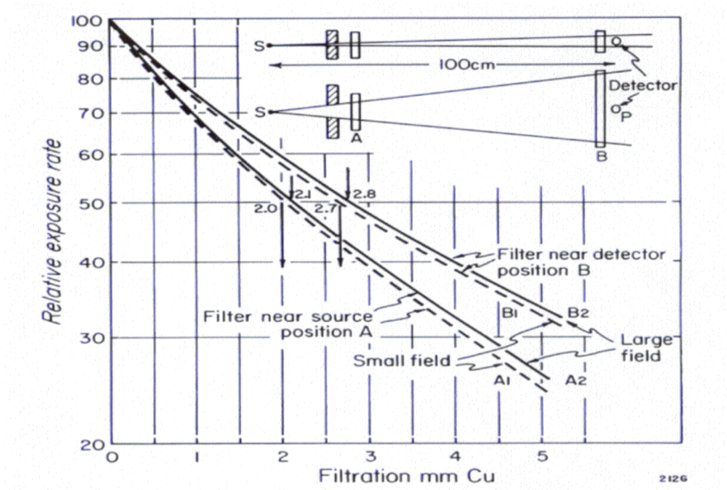


fig. 1.4. of [7]
With the same side conditions, the field with the larger divergence achieves a higher percentage depth dose.

At the same time, it is shown that the position of the pre-filtering also has a significant influence: pre-filtering close to the focus leads to a higher percentage depth dose.

The percetage depth dose to be expected is a benchmark for selecting the x-radiation quality for effective exposure of the target volume, but also for reducing the radiation exposure of non targeted tissue.

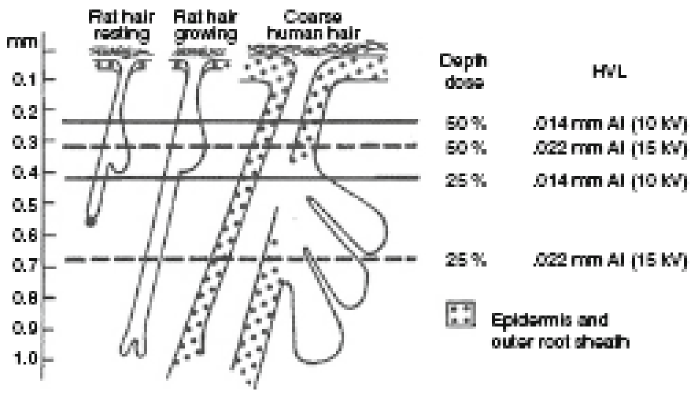


fig. 1.4 of [3]
Shows the depth structure of human skin and the effect of certain HVL on the dose load of the hair root.

Targeted selection of particularly "soft" x-radiation quality enables high doses on the surface with a steep dose drop at depth.

In the range of GRT and SXR energies up to 100 kV different absorption coefficients can clearly be observed. These absorption coefficients and the dose drop in depth, which can be easily selected in this energy range by parameters, allow options for therapy concepts that protect tissue outside the target volume and outside the target depth.

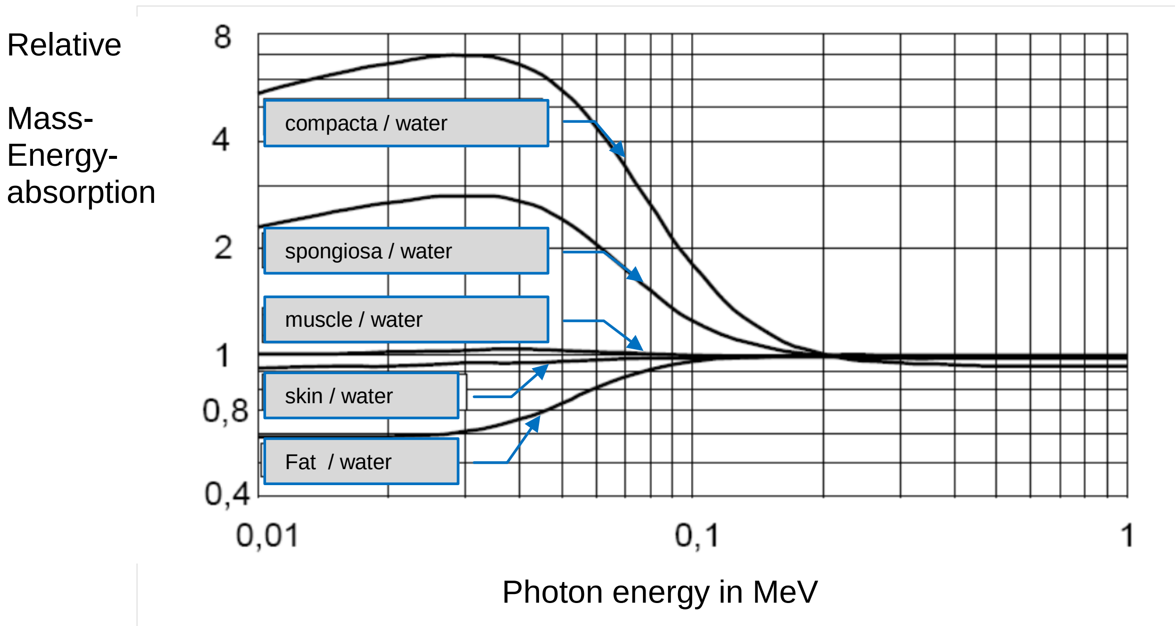


fig. 1.5 of [6]
shows different absorption coefficients in an energy range from 10 …. 100keV

With GRT and SXR energies, absorption ratios to water of up to a factor of 8 can be observed.

Due to the projection of the beam angle, large fields can be displayed with large focus-skin distances (40 ... 50 cm) of the applicators. In addition, large fields refer to large target volumes (e.g. joints), the extent of which should be exposed in depth with the highest possible percentage of the skin entry dose. In addition to the dependence of the relative depth dose on kV and pre-filtering, the field sizes also contribute to the percentage depth dose.

The following selection criteria apply:

cause		effect	
Applicator field size	↗	Area and volume of the target	↗
Applicator field size	↗	PDD	↗
FSD	↗	PDD	↗

2. Influence of the field size to the percentage depth dose

The effect of the field size-dependent backscatter described in (1) causes a significant influence of the field size to the relative depth dose.

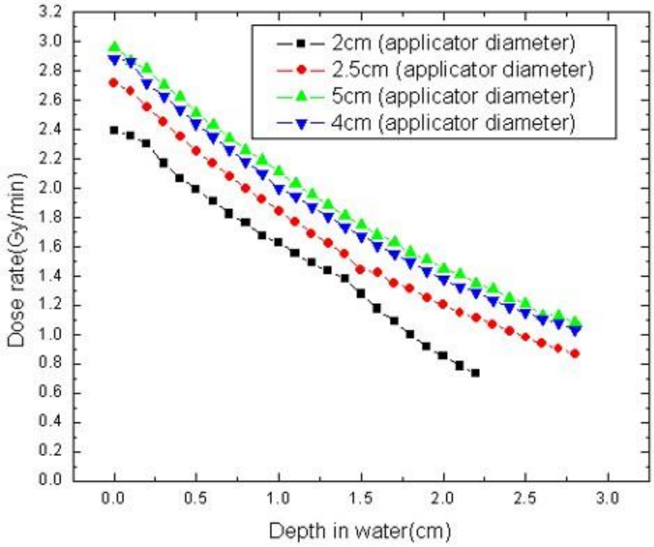


fig. 2.1. of [8]
depth dose rate for X-ray beams using different applicator diameter, plotted as a function of depth in water.

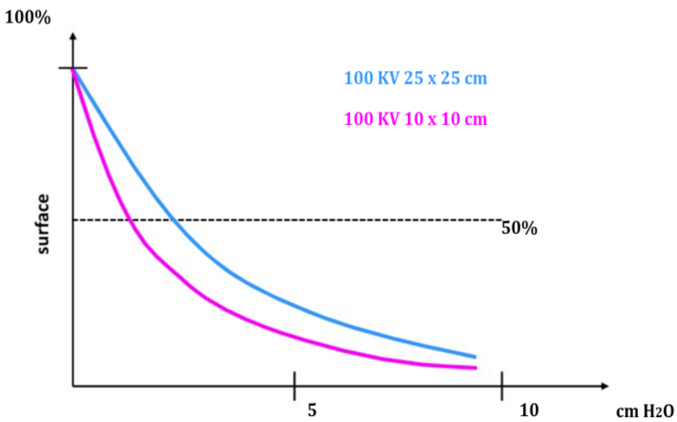


fig. 2.2 represents the effect of the field size-dependent depth dose with constant x-radiation quality.

It becomes clear that the larger-area applicator emits the significantly larger percentage depth dose under constant edge conditions.

Especially in the GRT and SXR energy range, in which primarily soft spectra with a steep drop in depth dose are preferred in the treatment of skin diseases, large-area applicators and usually associated with them with a significantly larger FSD are **not** indicated because of the increased depth effect.

3. Influence of the FSD to the percentage depth dose

Due to the divergence, the dose rate decreases quadratically with the distance from the focus (square law of distance). As a result, the percentage depth dose increases with increasing focus-skin distance under constant edge conditions.
The explanation of this effect is shown in Fig. 3.2.: The percentage depth dose at point B increases with increasing FSD due to the inverse square law relative to the dose at point A which was set to 100%. Added to this is the beam hardening of the x-rays due to the longer air column with increasing FSD.

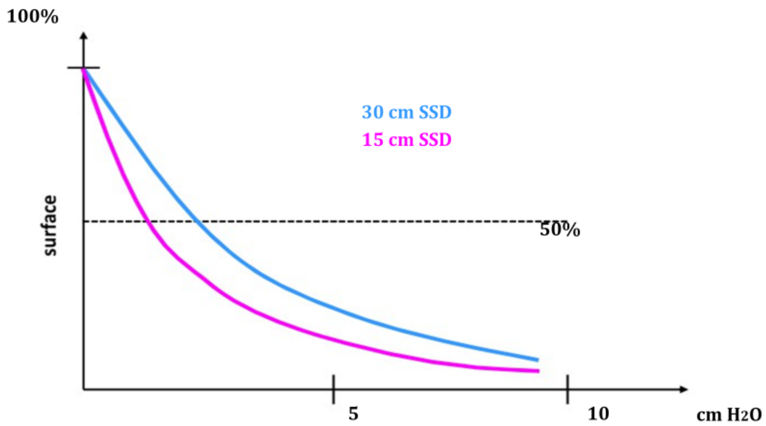


fig. 3.1. shows the relationship between FSD and percentage depth dose.

It becomes clear that the applicator with a larger FSD delivers the significantly larger percentage depth dose under constant edge conditions.

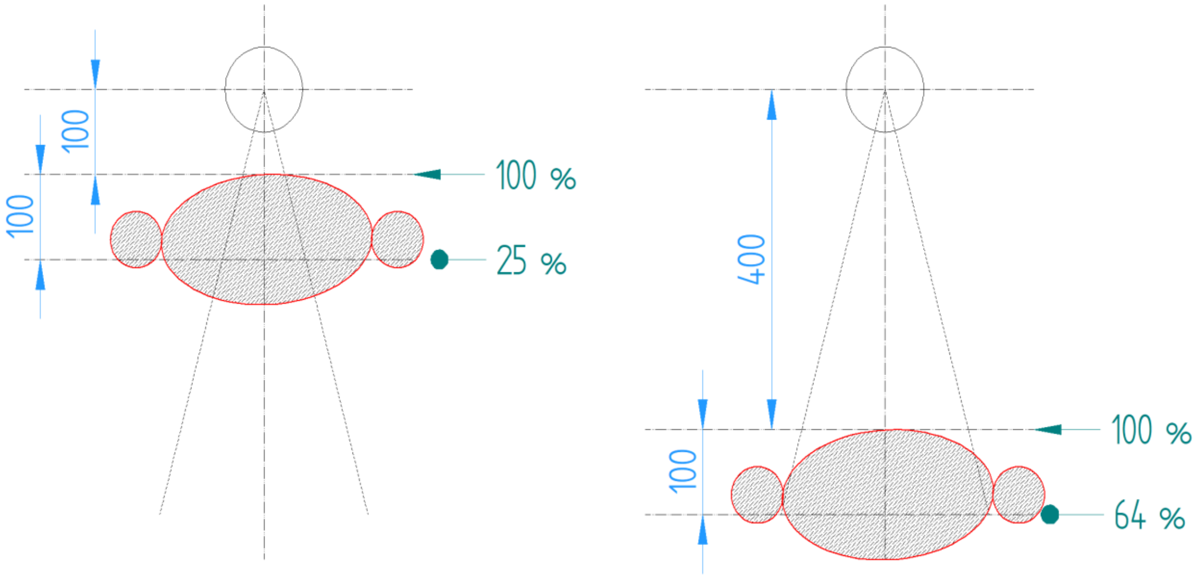


fig. 3.2 Schematic representation of the influence of the FSD to the percentage depth dose [13]

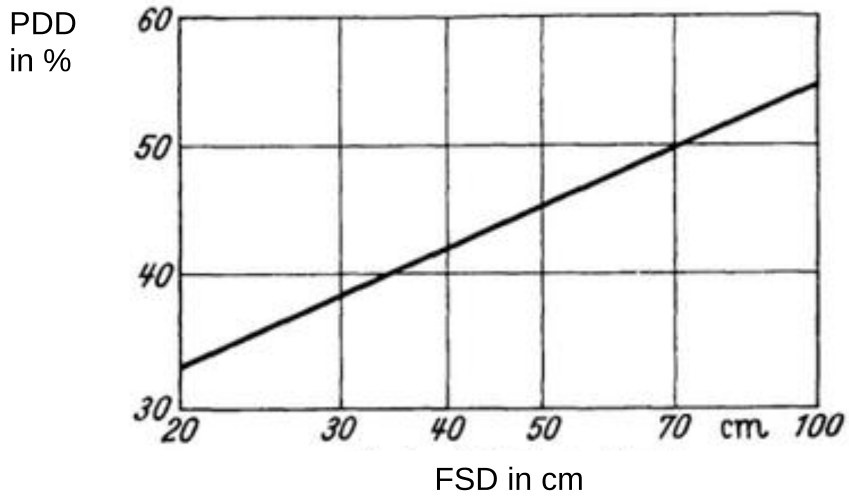


fig. 3.3. Influence of the FSD to the percentage depth dose at 200 kV [13]

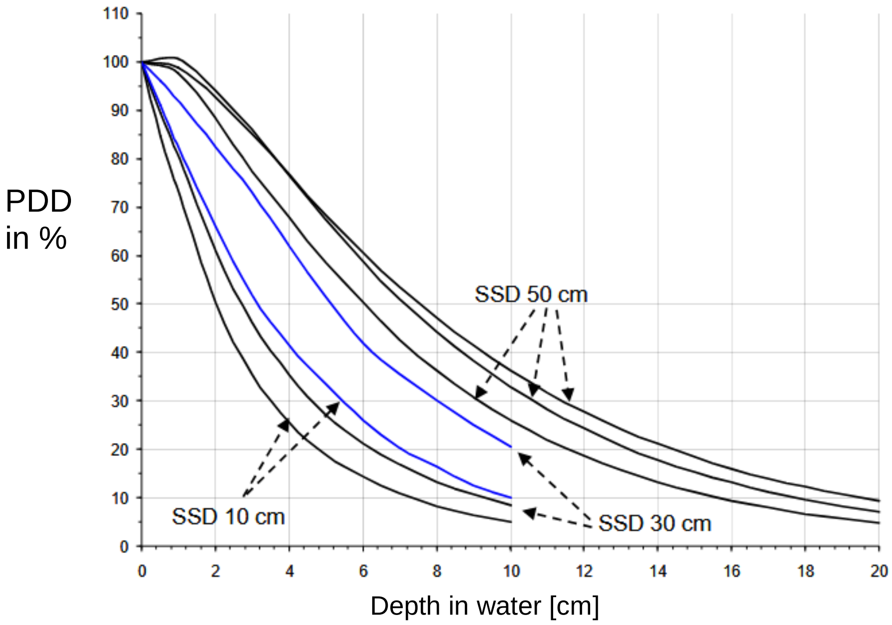


fig. 3.4 Experimental depth dose curves [14] (with data from [10])

displayed are Applicators with FSD 10 – 30 – 50 cm and a field size of d=10 cm
and HVL von 2 Al – 8 Al – 0,5 Cu – 1 Cu – 3 Cu

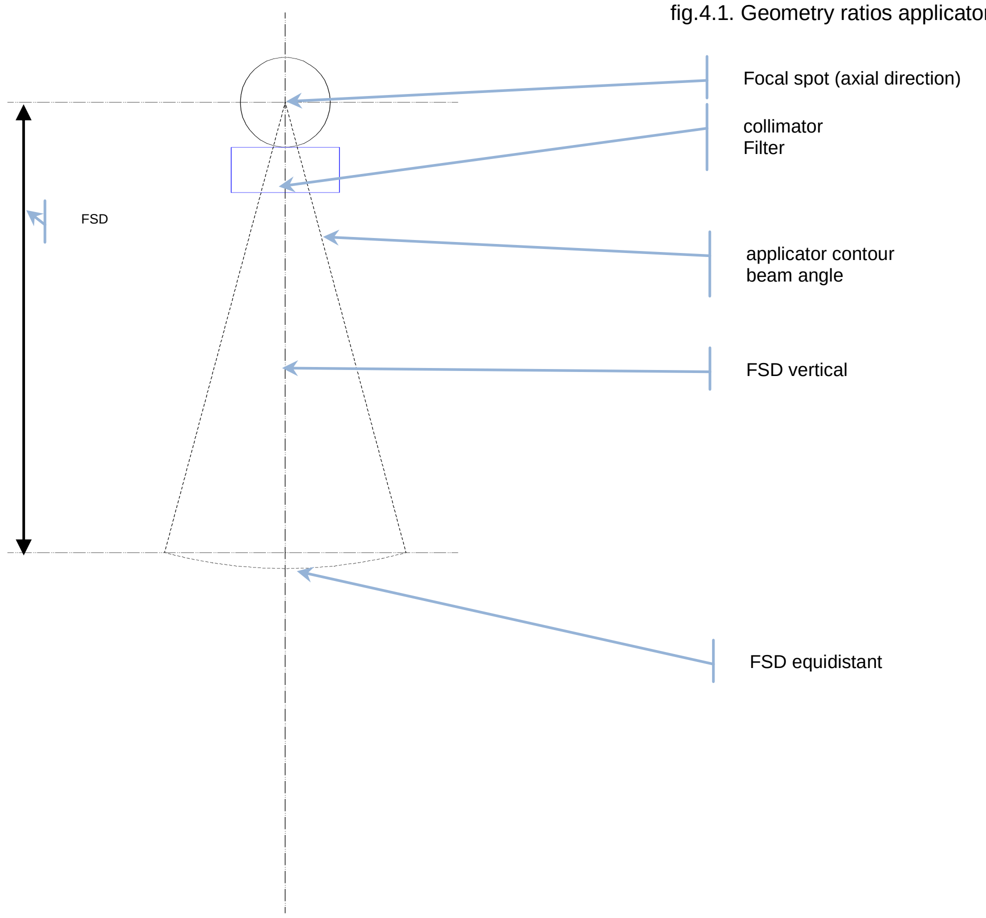
Especially in the GRT and SXR energy range, in which primarily soft spectra with a steep drop in depth dose are preferred in the treatment of skin diseases, applicators with a large FSD are **not** indicated because of the increased depth effect, since the increased depth effect is not intended in superficial x-radiation therapy.

4. field homogeneity and field size

The therapeutically required field size is essentially determined by the expansion of the target volume in the therapy level plus a safety margin.

Due to the type of X-ray radiation generation, a dose distribution is generated at an equidistant distance from the focus, which is characterized by a maximum in the central axis and a dose drop towards the edge. Technical solutions exist in which the equidistant FSD is approximated by a convex bulge of the applicator cap in the beam direction.

fig.4.1. Geometry ratios applicator



Despite the equidistant spherical cap in Fig. 4.2. is shown, that measured in the water phantom, there is already a significant edge drop there. Fig. 4.3 shows a comparison of applicators with smaller and flat surfaces. The edge drop is analogous to Fig. 4.2.

If the spherical cap is designed flat in the FSD plane, the difference in distance between the central axis and the edges of the field, depending on the size of the applicator field, leads to a further occurrence of the edge drop.

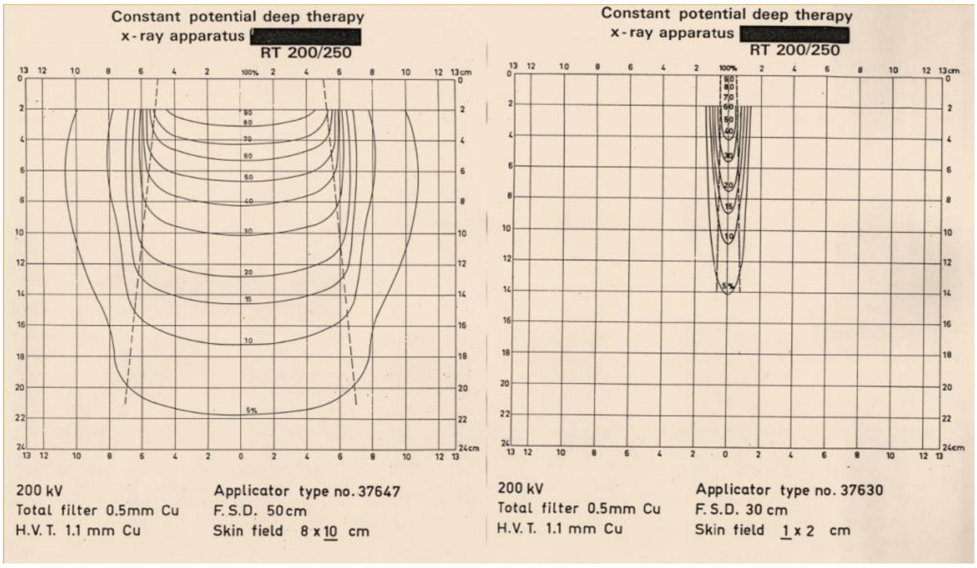


fig. 4.2. of dose distribution RT250 Philips at 200 kV

Field size 10 cm Field size 1 cm

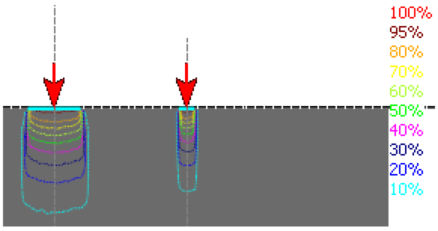


fig. 4.3.
MC Simulation [12] for applicator at 100 kV/4 mm Al

- D5 / 30 left
- D1.5 / 25 right

The lower percentage depth dose and the clear edge drop with the tube D1.5 / FSD 25 are clearly recognizable

Fig. 4.4. shows the dose distribution on an 8 x 10 / 40 applicator. The edge drop runs concentrically towards the edge and can be 15 to 20%, possibly reinforced by the heel effect [11], for very large fields.

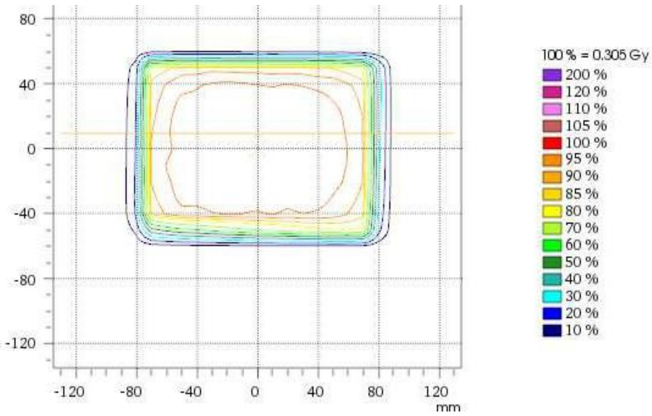


fig. 4.4 Dr. Christoph Baum, 09.05.2017, Schwarzwald-Baar Klinikum Villingen-Schwenningen
with PTW 2D Array measured dose distribution at the surface of an applicators 8 x 10 / 40

In order to achieve reproducible homogeneity even for large fields, it is helpful to cut out a homogeneous confidence region from a larger field (e.g. with a rubber lead cut out). This also makes it easier to fade out in the radiation field appropriately for the object.
The technique of fading out in homogeneous field sections from a full field also makes the availability of narrowly graduated applicator field size series obsolete.
The constant, reproducible distance to the focus is only given if the exit surface of the applicator lies completely on the tissue surface. This is guaranteed in particular when using flat spherical caps whose FSD is shown in the central axis. Furthermore, the closed spherical cap prevents tissue from ingression (e.g. through compression) into the applicator body and thus from shortening the FSD.

5. Dose contribution from secondary electrons

From [1] quote: *“Foreign radiation, consisting mainly of secondary electrons, can emanate from the inner walls of the applicators used in radiation therapy, which leads to an increase in the tissue surface dose with X-ray tube voltages above 50 kV. The influence of EXTERNAL RADIATION on the measurement result can be largely eliminated by placing a plastic foil about 0.1 mm thick. The film material used should be approximately water equivalent. The level of the dose contribution generally increases with increasing tube voltage, but it also depends on the design details of the APPLICATOR and its condition. The foil should also be used in the RADIATION of PATIENTS.”*

Applicators made of metal for applications with tube voltages > 50 kV must be sealed with a foil (household foil) or a PMMA spherical cap to prevent secondary electrons from occurring. Secondary electrons are absorbed in these thin plastic layers and their contribution becomes clinically insignificant for the upper layers of the skin. The use of a thin, transparent film made of polyethylene (PE) for single use also improves the hygienic component in patient contact and can therefore be used with all applicators.

The attempt to achieve less hardening of soft X-rays with open applicators is already defeated by the filter effect of the air column.
Furthermore, the closed spherical cap prevents tissue from ingression (e.g. through compression) into the applicator body and thus from shortening the FSD.

6. Reproducibility of the FSD

Applicators with a fixed field size and fixed FSD guarantee high reproducibility of the beam geometry in fractionated applications.
In order to prevent superficial tissue contours that are smaller than the field size of the applicator from ingression into it, spherical caps help to close the applicator in the plane of the FSD, but allow the X-rays to pass through almost unattenuated due to their low density .
The spherical cap also allows the tissue to be treated to be compressed and thus provides an equidistant surface for the therapy.

For reasons of reproducible dosimetry, applicators with field sizes > Ø 3 cm are generally used in a closed design (with PMMA cap). The risk that tissue parts or parts of the extremities can ingress into the applicator body, shortening the distance and thus increasing the dose uncontrollably, is effectively controlled with a PMMA cap. There is no negative influence of the PMMA cap to the X-ray spectrum.

7. Therapeutic safety margin

Fig. 7.1 shows the relationship between the safety margin and the possible tendency to recurrence in the superficial x-radiation therapy of skin carcinomas. It has been shown that with a safety margin of 15 mm around the delimited tumor, a probability of almost 100% can be achieved to have detected all tumor cells in the radiation field.

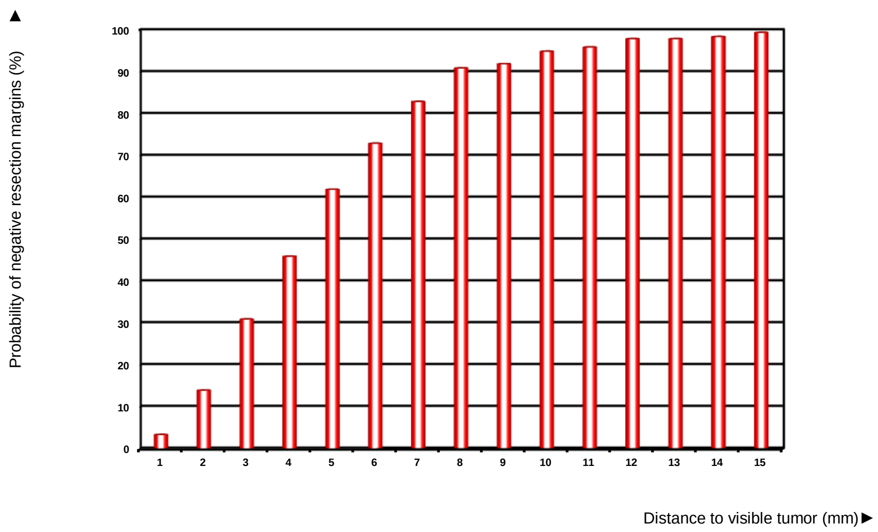


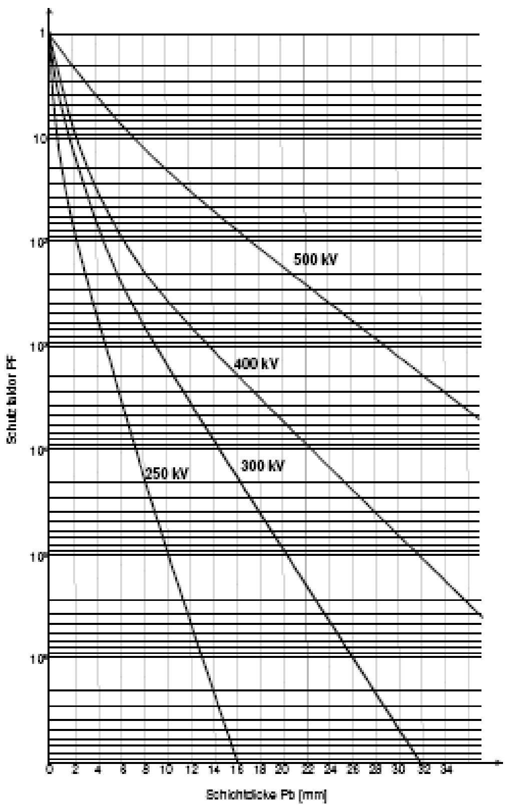
fig. 7.1
Probability of negative resection margins (%)versus distance to the visible tumor (mm)
M. Notter, 09.05.2013 - Radiotherapie bei malignen Hauttumoren: Interdisziplinäre Optionen bei Basaliomen und Plattenepithelkarzinomen der Haut (Choo et al; IJROBP 62, 1096-1099, 2005)

Fig. 7.1 shows that applicators with field sizes < Ø 2 cm do not allow the necessary control of a safety margin even for the smallest target areas. Field sizes < Ø 2 cm continue to lead to the situation already shown inhomogeneity in Fig. 4.2.. For therapeutically necessary applications < Ø 2 cm, lead rubber insertions with a larger applicator field area are the means of choice. An exception here are special anatomical situations (mostly in the head and neck area), which cannot be reached with large-area applicator fields.

8. Shielding outside applicator field limits

Applicators are used to shield against direct radiation outside the field intended for therapy. The conditions for the shielding effect are described in [2]. The shielding effect of the applicator fade-in close to the focus depends on the radiation quality, defined by tube voltage and pre-filtering. The tube voltage has an exponential effect on the dose rate, which must be reduced to 0.5% in the FSD of the applicator according to [2].

shielding factor (log) ▼

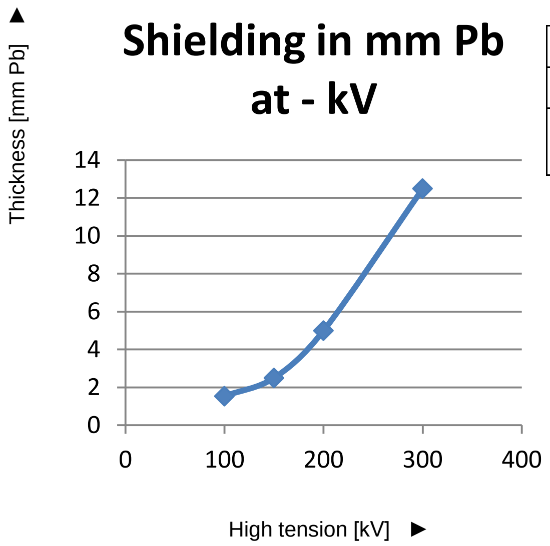


thickness [mm Pb] ►

fig. 8.1. protection factor PF for x-rays up to 500 kV (filtration: 0.5 mm Cu for 250 kV und 3 mm Cu für 300 kV).

from Stephan Scheidegger
Paul Scherrer Institut,
Grundlagen der Strahlenphysik
und Dosimetrie (Röntgenstrahlung)

High tension [kV]



100	150	200	300	**kV**
1,54	2,5	5	12,5	**mm Pb**
548,8406	890,975	1781,95	4454,875	**Pb [g] weight**

Tab.:
Influence of shielding thickness to the applicator weight.

fig. 8.2
Minimum shielding for collimation in relationship to the high tension

A lack of limitation of the applicable X-ray energy range has a negative impact on the design of the applicator weight. The necessary shielding, especially with high tube voltages, adds to the applicator's own weight.
The relationships from point 2. and 3. make it clear that there is a connection between "small" energy (GRT, SXR) and the use of applicators with relatively smaller field sizes and FSD in contrast to the use of "large" energy (DXR) with applicators with relatively large field sizes and FSD. Since the distance in applicators with a large FSD has a significant impact on the overall shielding, weight can also be saved with the application-oriented concept.

The following selection criteria apply:

cause		effect	
High tension (tube voltage)		shielding applicator	
applicator shielding		applicator weight	
Applicator FSD		applicator weight	
High tension (tube voltage)	Applicator FSD max. kV: 100, 150, 200, 300 FSD [cm]: 20 … 25, 30... 40, 40 ... 50, 50		

Conclusions

Applicators with a fixed focus-to-skin distance (FSD) and fixed field size are the means of choice in modern conventional X-ray therapy.
The constructive properties and material properties of applicators are associated with preferences both for dosimetric effects and for therapy concepts, which must be taken into account when preselecting applicators. The selection of applicators is a point in the optimisation of the objective radiation-physical edge conditions to be observed in conventional X-ray therapy and their targeted use in therapy concepts. The renunciation of superficial generalists (among the applicators) opens up a wide range of possible uses by exploiting the physical boundary conditions for a successful therapy.

Although the relevant guidelines occasionally refrain from specifying or limiting specific energies or geometry, the target volume to be treated already predetermines the energy, field size and applicator length (FSD) that can be used for treatment.

As has been shown, large-area and/or long applicators tend to have an increasing effect on the percentage depth dose distribution due to dosimetrically preferred edge conditions, so that the use of large-area applicators with FSD 40 ... 50 cm for orthovolt therapy (DXR) is contructive and guideline conform. The use of these applicators in superficial x-radiation therapy (GRT, SXR), however, leads to the therapy concept being thwarted. There, applicators with FSD ≤ 30 cm are the method of choice.

Inhomogeneous dose distributions and the effect of the increased percentage depth dose distribution with applicators with a large field area suggest the use of cut-out collimation to the object (lead rubber cut-out) in order to ensure a low depth effect at a sufficient safety margin for superficial x-radiation therapy (GRT, SXR). As a further advantage, the use of object near cut-outs can benefit from object-specific contouring. Modern planning systems support dose planning of irregular fields, taking their effects into account.

A simple guiding principle shows the relationship: **large applicators (FSD, surface) are used when a large percentage dose distribution effect is intended.**

Modern planning systems support the proper use of applicators
through restrictive selection restrictions in constellations that represent an increased risk.

In contrast to square or circular formats (possibly with the help of cut-outs), the selection of rectangular field formats proves to be more flexible.

The energy range (GRT ... SXR ... DXR) for which they are to be used is directly related to the applicator size. Limiting the energy that can be used allows the optimization of the applicators weight while maintaining their shielding effect. This favors the therapy concepts in superficial x-radiation therapy (GRT, SXR).

The closure of large-area applicators with spherical caps made of PMMA not only ensures high reproducibility of the FSD, it also makes positioning easier thanks to a transparent viewing surface, prevents the risk of overdosing at tissue ingressing in the applicator body and is preventing a dose-contribution by electrons. PMMA spherical caps are usefiul adaptive to hospitals hygiene concepts – they can be cleaned effectively. With the additional use of plastic film for single use, an excellent hygienic prognosis is given.

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