

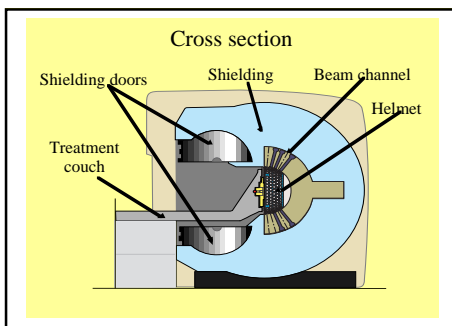
Gamma Knife Dosimetry & Treatment Planning

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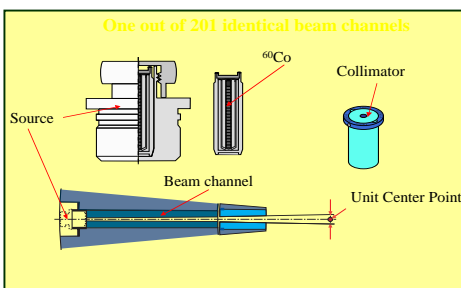
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Introduction

We are today in the process to understand how dose and dose distributions affect the outcome of radiosurgical procedures. There is clinical evidence that the peripheral dose is relevant to predict the outcome for AVM:s and that the entire volume that receives therapeutic dose is significant to predict side effects for the same indication. For tumors the mean dose is believed to be important for the outcome and the dose to surrounding normal tissue the factor on which side effects may be predicted. Therefore, as seen from a technical and a radiophysical perspective there are two important factors that earlier more or less have been based on intuition but now are resting on scientific ground. The radiosurgical procedure must be reproducible and the therapeutic radiation dose must be delivered selectively to the target volume.



Consequently the apparatus used for the irradiation procedure must be designed to permit reproducible treatments of the smallest volume (1 cm^3 or less). Considering the smallest lesion of the Gamma Knife we should aim at a total geometrical accuracy and precision of less than $\pm 0.5 \text{ mm}$. The most direct way to realize this aim is to keep all important parts of the treatment unit stationary during treatment.



Furthermore, those parts affecting the photon beam (collimators, source, etc.) must be carefully designed and optimized for the narrow beam size.

The steep dose gradient, characteristic for radiosurgical procedures, must be correctly simulated and described in the protocol by the treatment planning system with respect to dose distribution and geometry.

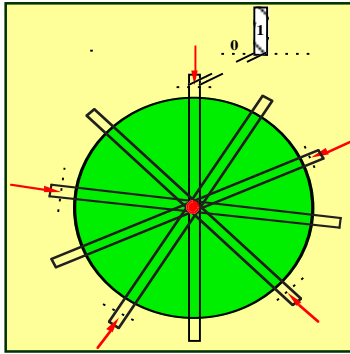
Here mainly attention is paid to the beam data that is pre-stored in Gamma Plan and to the hypothetical dose distributions whose calculation is based on this stored data.

Naturally in the clinic it is necessary to consider the entire chain of procedures. Starting with the quality of images, on which the simulated dose is overlaid and ending with the treatment by which the treatment plan is realized within the brain of the patient.

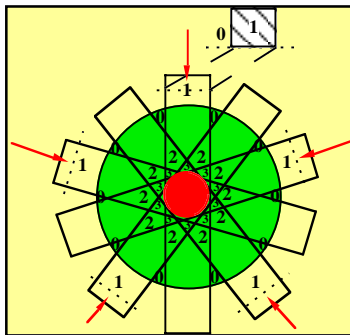
Irradiation technique

Some principal consequences

Convergent beam irradiation technique is used in radiosurgery to focus the radiation energy inside the target volume. This technique is also used in the Gamma Knife. It has some important characteristics.

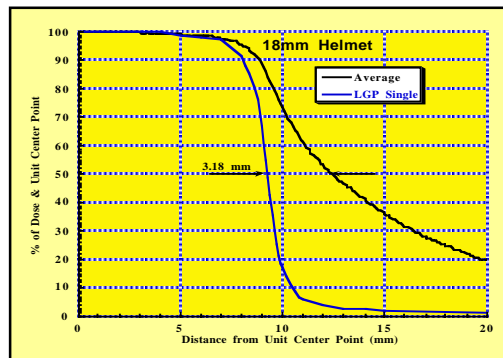
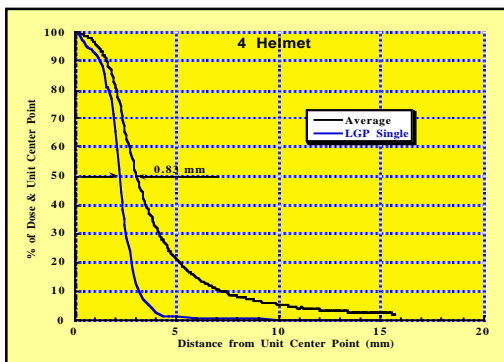


To the left are shown in two dimensions, the principles of this three dimensional irradiation technique. One illustration shows the situation when a small target is irradiated with narrow beams. The second illustration shows a large target covered by broad beams.



The characteristics of the 5 “digital” beams that are directed towards the target, are 1 inside the beam and 0 outside. In this example geometry is only considered and therefore attenuation, square law and scatter is omitted when studying how the beams penetrate the tissue (green) on their way to the red target.

As compared to the example with the small target, the broader beams used for the larger target start overlapping at a larger distance from the target border. A large volume of normal tissue receives then a therapeutic dose because the largest part of a given spherical volume is found at its periphery. From this oversimplification of reality we can conclude that radiation biology will mainly limit the largest size of the target volume that can be treated in a selective manner. Technical and radiophysical tolerances of the treatment unit will determine the smallest target that can be treated in a reproducible manner.

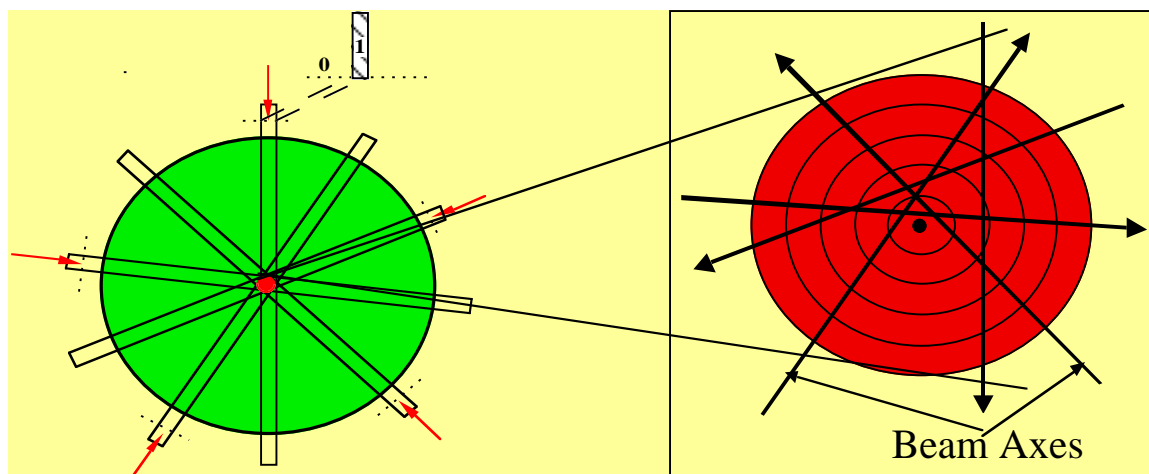


To illustrate this hypothetical discussion above with reality, Off Axis Ratios (OAR:s) of the smallest and largest single beam of the Gamma Knife are compared with corresponding OAR:s of the radio lesion where the contribution from all single beams is combined.

It can be seen that the penumbra of the two single beams is approximately the same in spite of the difference in beam diameter. In contrast differ the gradient at the borders of the resulting dose distributions considerably. The less steep dose gradient of the lesion irradiated by the larger beams is to a large extent a geometrical phenomenon.

Beam alignment

If the region where the radiation focus is said to be located is magnified, it can be seen that the beam axes do not cross exactly at one single point. This fact holds true for all treatment units independent of their technical design. The degree of magnification that is required to see this phenomenon depends however on the technical solution of the treatment unit as well as on its technical and radiophysical tolerances.



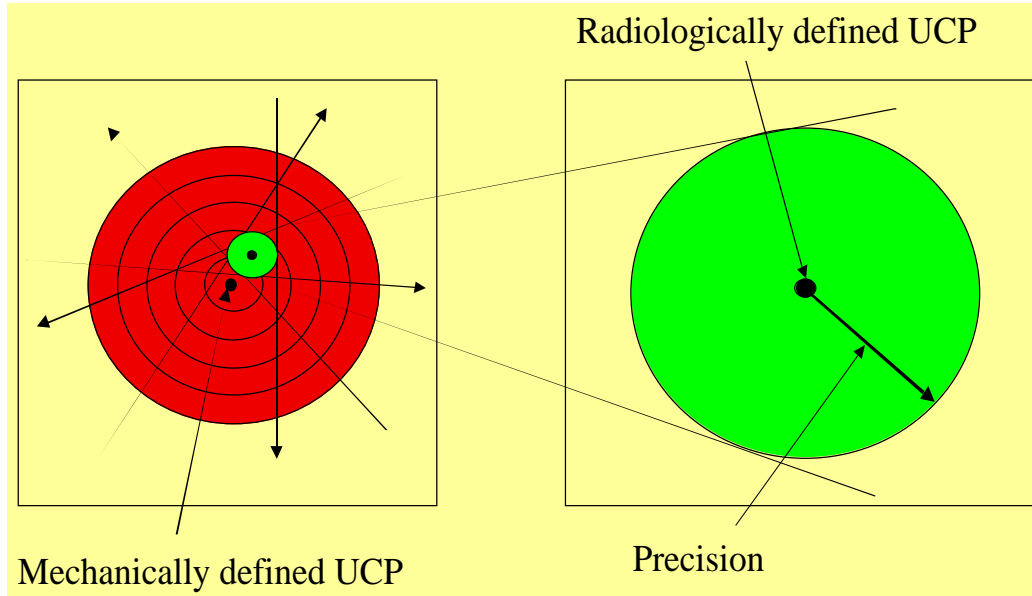
This beam miss-alignment has two consequences for the quality of dose delivery. The “center of mass” of the radiation focus may be dislocated in relation to what is assumed, leading to a geometrical error in the dose delivery. The dose distribution may also differ from what is the ideal one; that is, the dose is smeared out over a larger region and its magnitude being less than calculated by the treatment planning system.

The existence of these errors is acceptable, provided they are kept so small that they have no clinical significance during the life of the treatment unit. An eye must therefore be kept on these errors by means of QA-controls. It is obvious that it is easier to obtain and

to maintain narrow geometrical tolerances with stationary beams as compared to a mobile system, subject to wear and tear.

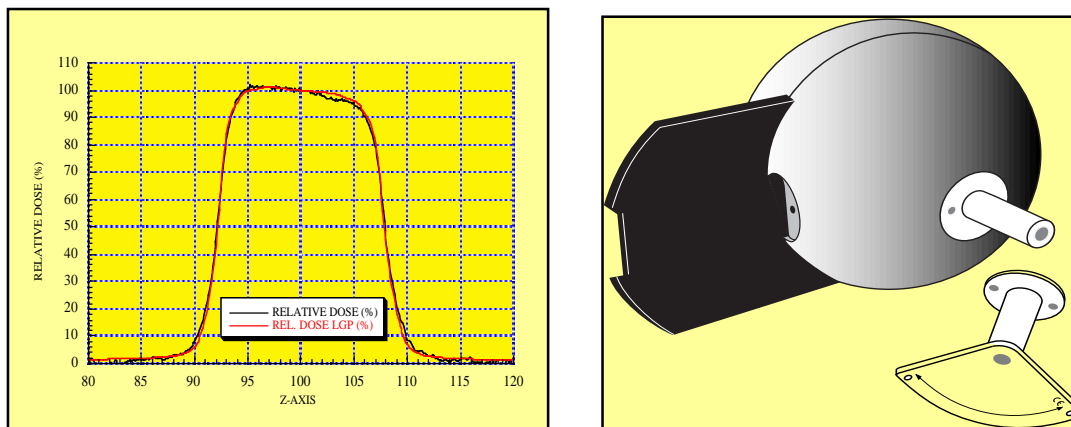
Gamma Knife precision and accuracy

We may define the center of the smallest sphere through which all beam axes pass as the radiological Unit Center Point (UCP) or isocenter. The radius of this sphere may then be seen as a measure of the spread of the beam axes or the uncertainty of their location. This uncertainty is called “the precision of the Gamma Knife”.



It is a time consuming task to calculate the precision of the Gamma Knife by using the tolerance measurements of all relevant parts made during the manufacture of the unit. Instead a more direct and practical solution may be chosen.

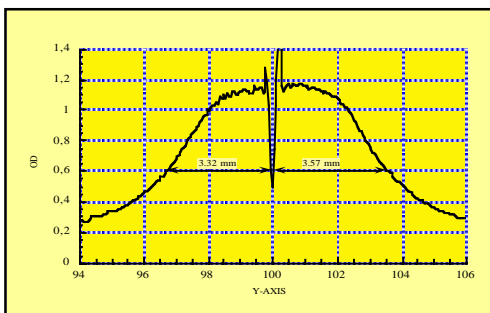
Measured dose profiles are compared with those calculated, assuming identical conditions. The only disadvantage with this approach is that the experimental error of the



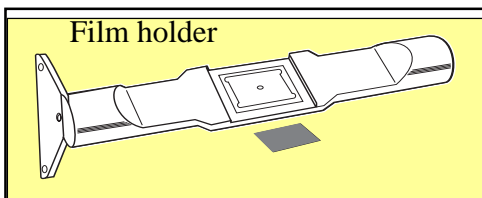
used film dosimetry is by far larger than the radiological consequences of the beam alignment we are looking for. Thus, the experimental error rather than the beam alignment determine the tolerance set for the measurement of the precision. The used tolerance of ± 0.5 mm for each of the three axes is questionable as seen from the clinical perspective, but it is the best we at present can do in daily routine

A spherical phantom simulating an adult human head is used for the film exposure. The films can be placed at the center of the sphere and the sphere can be rotated so that the film planes are correctly orientated in relation to the stereotactic system.

The distance between the mechanically defined Unit Center Point and the one defined by radiological means is called "The Gamma Knife Accuracy". This deviation is determined



by measuring the distance between the radiological and mechanical Unit Center Points. This measurement is made along the three perpendicular axes of the stereotactic frame.



The spherical phantom can not be manufactured with sufficient narrow tolerance to be used for this measurement. Instead are films exposed in a very accurately machined tool in which the mechanical Unit Center Point is simulated by a sharp needle. The needle is used to pierce the film. The hole in the film is then compared with the location of the center of the optical density distribution.

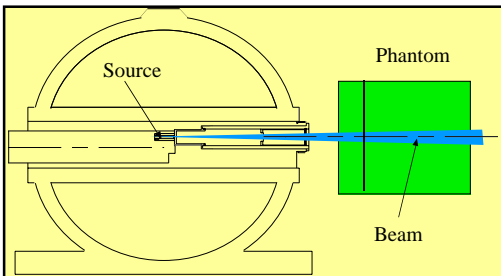
Beam data stored in Gamma Plan

All beam channels of the Gamma Knife are manufactured to very narrow mechanical tolerances. If allowance is made for the decay of the 60 Cobalt, these beam channels may be considered identical and unchanging from a radiophysical point of view. The design of the Gamma Knife is such that all beam channels of the same size are identical, independent of the individual unit or its model. This means that the storage of beam data in the treatment planning system GammaPlan can be greatly simplified. This is a great advantage since it would be difficult, to measure individual beams to the required accuracy inside the unit on site. Despite the simplicity of pre-storing the beam data, this approach has one disadvantage. It requires that the users, must trust in the reliability of this data at any specific installation.

The following radiophysical data is pre-stored in Gamma Plan.

- 4 beam profiles (OAR:s), one for each beam sizes measured at 400 mm distance from source center and at 80 mm depth in polystyrene.
- One data set to analytically calculate Percentage Depth Dose (PDD)
- 4 measured factors compensating the beam size dependence of the dose rate, the so called OutPut Factors (OPF)

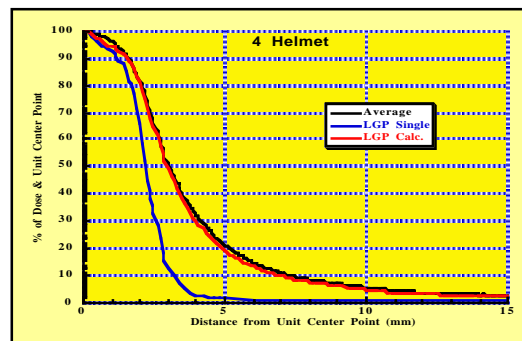
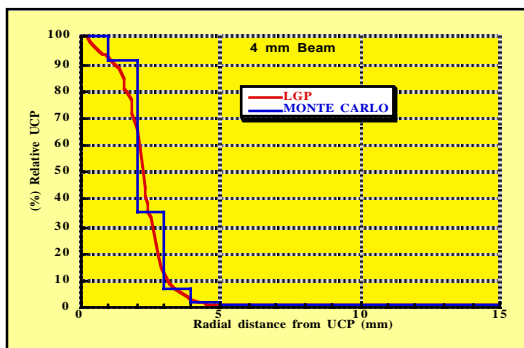
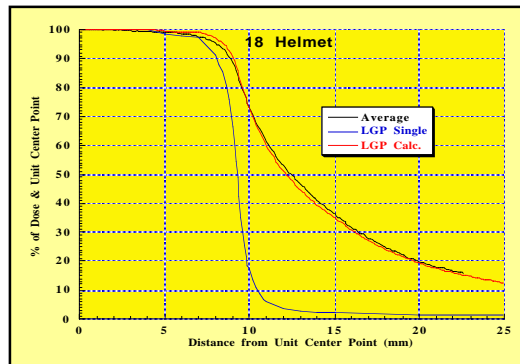
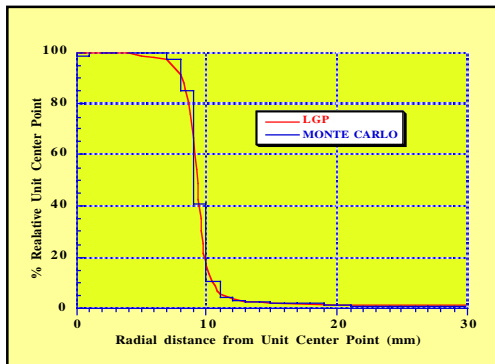
The experimental beam channel



It is inconvenient to measure single beam data inside the Gamma Knife. In addition it is difficult to obtain the required accuracy of the measurement. Instead a specially designed experimental device is used when the data stored in Gamma Plan is measured. The design of the device is such that exact copies of any of the

beam channels of the Gamma Knife can be inserted. Data measured in a horizontal beam can thus accurately and conveniently be made. The low dose rate of one single source requires that radiographic films are used instead for chromatographic films.

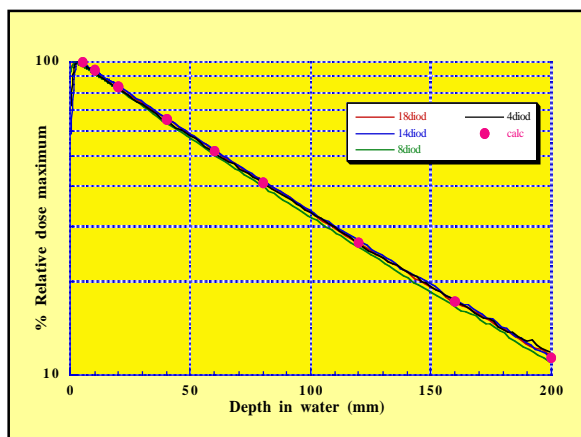
Off Axis Ratios



Diagrams 1 and 3 above show measured and MC-calculated OAR:s of the 18 mm and the 4 mm single beams. The measured single beam OAR:s for all 4 helmets are pre-stored in Gamma Plan.

It is obvious that the chosen resolution of the MC-calculations is too sparse, and is therefore of limited value to validate measured data, at least in the important penumbra region. Instead are the measured single beam OAR:s used to calculate the combined dose distribution that then is compared with corresponding measured OAR:s. This comparison is shown in diagrams 2 and 4. In order to reduce experimental uncertainties, an average OAR from 10 recently commissioned units have been used. Although only comparisons for two helmets are shown here, minor deviations between the calculated and the average of the measured OAR:s can be seen for all 4 helmets. None of these deviations are however of any clinical significance.

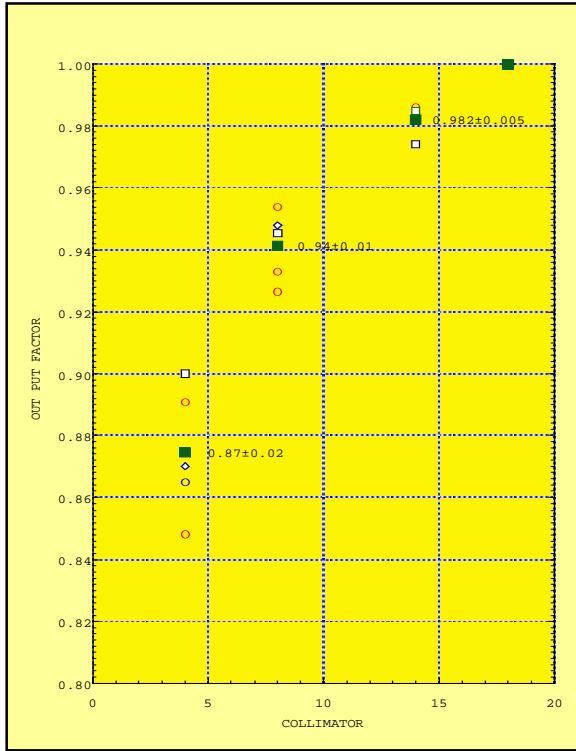
Percentage Depth Dose



As the distance between the source and the Unit Center Point only is 400 mm, the inverse square law dominates over the beam size dependent attenuation. In fact the change in attenuation is small for these very narrow beams. Thus, one single attenuation coefficient may be used for all 4 beams when the Percentage Depth Dose (PDD) is calculated. In order to verify this assumption, PDD:s were measured in water by means of a semiconductor and using the experimental device. In the left diagram PDD:s for all 4 single beams are compared with calculated data. We can conclude that the word “assumption” can, at least for clinical purpose, be changed to a statement.

OutPut Factors

The third data set that is pre-stored in Gamma Plan is the factors correcting the dose rate for its dependence on beam size, that is, the so called OutPut Factors (OPF). These 4 factors are based on dose rate measured at the center of the spherical phantom that is aligned at the Unit Center Point. The dose rate thus measured is normalized to the dose rate measured in the 18 mm helmet.



It is obvious that there are some experimental difficulties involved in measuring the dose rate in the 4 mm helmet. It is even more difficult to measure it on the beam axis of one single beam. The OPF for the 4 mm helmet is therefore subject to the largest uncertainty as compared to the other OPF:s. The numerical value is also subject to some controversy.

Numerical values ranging from 0.63 to 0.93 have been measured. The size of the sensitive volume of many detectors and their alignment are two common errors. Most of the experimental errors will result in a value that is too low.

The “new” OPF:s are based on fairly recent data measured at different sites in Europe. The data is averaged from measurements with TL-detectors, liquid ionization chamber and semiconductors. The extremes of these measurements have been excluded. The data and its average are shown in the diagram to the left. The only value that significantly deviated from the earlier recommended OPF:s is the one for the 4 mm helmet, which is changed from 0.80 to 0.87.

How relevant is the assumption that the OPF:s are the same for all units, independent of their age or model. Careful measurements have been made in five B-model units of different age and also in single beams of the experimental device. These measurements confirmed that there are no measurable differences between the five units or between the measurements in the units and in the single beams. It can therefore be concluded that there are no measurable differences as long as the design of the beam channels is the same, which means that there should be no difference between the U-model and the B-model.

Collimator	4	8	14
Analytical ¹⁾	0.871	0.943	0.979
Monte Carlo ²⁾	0.879	0.960	0.979

1) P.Nizin, Med. Phys. Dec. 98
 2) S. Liu, Karolinska Hospital

The range of published calculated OPF:s for the 4 mm helmet is similar to those measured. The very selected data of the table to the left is chosen for two reasons. The analytical data is

the most recent publication. The data from the Karolinska Hospital is the only MC-calculation into which I had some insight how it was obtained.

18 mm helmet	1.00
14 mm helmet	0.98
8 mm helmet	0.95
4 mm helmet	0.87

The OPF recommended by the manufacturer of the Leksell Gamma Knife are shown in the table to the left.

The used detectors have all their limitations			
Detector	Si	TLD	Liquid
Small volume	+++	-	++
Energy independence	--	+	+++
Dose rate independence	+++	++	++
Directional independence	-	+	+++
High signal/volume ratio	+++	+	+++

The table to the left is an attempt to describe relevant characteristics of the used detectors with respect to dose measurements in very narrow beams. The number of plusses or minuses are by no means statements - rather indications. It can be seen, also with this

crude classification that the liquid ionization chamber is superior for measurements in narrow beams. The only reason why the data for the OPF:s are not based only on measurements with the liquid ionization chamber is that there at present exists little practical experience in narrow beam application.