QUALITY ASSURANCE IN RADIATION TREATMENT PLANNING. PRINCIPLE CONSIDERATIONS AND A PRACTICAL PROPOSAL.

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INTRODUCTION

While detailed quality assurance based on standard protocols is mandatory in external beam radiotherapy for treatment machines, dosimetry, dose specification and recording, no standard protocols are known for radiation treatment planning. Users of treatment planning system have, to some extent, introduced their own system checks, but usually one relies on hand calculations to verify doses to reference points in a patient treatment plan. Also, there appears to be at present a wide-spread belief that the application of treatment planning systems in the daily routine will be sufficient to reveal any deficiencies the system might have. A few attempts have been made to introduce formalized quality control (QC) protocols for treatment planning (Rosenow et al, 1988; Rosenow et al, 1989), and specific investigations in this problems have been reported (Mc Cullough and Krueger, 1980; Rosenow and Burmester, 1978; Rosenow, 1977; Rosenow et al, 1984; Rosenow et al, 1987; AAPM, 1995). Obviously, there is an urgent need for standardized QC protocols in treatment planning systems.

However, there exist fundamental obstacles to quality assurance in radiation treatment planning systems. Such systems can only reproduce accurately, i.e. within the tolerance of the system, the data directly entered into the system, e.g. measured beam dose distributions. Essentially all other calculations of dose distributions are estimates, or rather predictions, in terms of the real dose distribution in the patient or phantom, of what will results from a specific irradiation technique. Therefore, the goal for QC in treatment planning can only be to establish confidence in calculation results which are, in principle, not verifiable.

MATERIALS AND METHOD

In the approach proposed below confidence in the reliability of treatment planning system is established by checing out a limited range of results which are verifiable, e.g. by comparison of calculated with measured dose distributions, and by some additional plausibility considerations. In other words, the philosophy for the development of a QC protocol in treatment planning needs to account for two basic facts: (i) The number of verifiable treatment planning applications is, in principle, unlimited. (ii) The additional time and personnel needed to run a QC protocol, is very much limited. Therefore, it appearts to be reasonable to let a practical QC protocol embody the following test cases:

a) Regular tests of all local data entered into the system.

b) A systematic compilation of a very limited set of carefully selected applications which allow the testing of basic characteristics of the system.

c) A collection of special test situations which are added to the compilation whenever they come up and are considered sufficiently general, or when a need is seen to check out an unusual system behaviour.

Quality assurance treatment planning systems, as generally in other systems too, may be subdividied into four test categories:

1. Pre-acquisition/system comparison checks.
2. Initial systems checks (ICRU 42).
3. Repeated system (ICRU 42)/Constancy checks.
4. Intermediate system checks.

In pre-acquisition checks the future user wants to find out which system might best fit to his or her needs. Such checks usually involve a system comparison. Test categories 2. through 4. are typical in-house tests and have quite different aims than has category 1. They should be performed by means of a local QA protocol. According to ICRU Report 42 initial system checks consist of the reproductions of input information, e.g. computation of beams for which data have been entered and the calculation of a set of selected example treatment plans, while repeated system checks consist of the calculation, at regular intervals, of a set of the selected examples covering range of irradiation techniques of the radiotherapy department. ICRU does not mention intermediate system checks which are

here considered as important to be run following any system or data modyfications, repairs, or service activities. They encompass any subset of the initial system checks from spot checks up to the full test range depending on the nature of the intervention.

According to the two categorial groups described above two different approaches for quality assurance protocols are presented in detail.

I.Data and Plan Library

For the purpose of pre-acquisition checks as well as system comparisons a Data and Plan Library is under development by a German task group. It consists of a systematic compilation of a strictly limited and carefully selected set of applications which allow the evaluation of basic system characteristics, amended by a few typical clinical treatment plans. Beam data consist of a depth dose curve and five profiles as well as an isodose chart. This data will be available in graphical, tabular and electronic form. A check of the off-axis calculation is also provided while more sophisticated techniques such as 3D conformal therapy are deliberately excluded.

For the clinical cases, to-scale cross-sectional drawings and details of the techniques as well as best-knowledge isodose plans are made available. Table I lists the set of basic beam data which will be provided in the Beam and Plan Library.

Table I.
Test cases assembled for the Data and Plan Library.

1. Single beam data:

One depth dose curve (DDC), five cross-beam profiles (CBP's), test line profiles (TLP's, some of which are identical with the CBP's), and isodose charts (IDC's) as in the listing.

Normalization always in d_{max} on central axis.

All measurements in shortest possible time and with intermediate checks of the sensitivity of the measuring equipment.

Field size definition via cross-beam profiles at 10 cm depth, with 45^0 oblique field in vertical position (then swing), with wedged field after removal of wedge.

Point raster for DDC's and CBP's: 2 mm.

CBP's are made symmetric.

SSD's:	Cobalt-60:	80 cm (=isocenter)and 100 cm for one 10 x 10 cm^2 field
	8 and 25 MV:	90 cm (100 cm SAD) and 100 cm for one 10 x 10 cm^2 and a 10 x 10 cm^2 /45^0 field
Fields:	DDC's:	4x4, 5x5, 6x6, 7x7, 10x10, 20x20, 30x30, 40x40 cm^2
	CBP's:	4x4, 6x6, 10x10, 20x20, 30x30, 40x40, 30x6 cm^2 ($d_{max,only}$)
	IDC's:	4x4, 6x6, 10x10, 20x20, 30x30, 40x40, 30x6, 6x30 cm^2
CBP depths:	Cobalt-60:	0.5, 5.5, 10.5, 15.5 and 20.5 cm
	8MV:	2, 10, 18, 26 and 34 cm
	25 MV:	3.5, 10, 16.5, 23 and 29.5 cm
Additional:	TLP's:	CBP's for 10x10/100 SSD at d_{max} and at 10.5 resp. 10 cm depth

2. Treatment Plans

All graphical input information is provided to scale.

Single „trangential" 10 x 10 cm^2 beam under 45 o on a circular cross-section (resembling, e.g. a head, neck or breast field).

Single 10 x 10 cm^2 beam impinging on a sinoidally curved surface (to demonstrate the ability to correct for curvature).

360^0 arc with axis at center of circular cross-section of 30 cm diameter, field 10 x 10 cm^2.

Four field isocentric technique centrally on pelvic cross-section (from Rando Phantom), fields 10 x 10 cm^2.

Two excentric lateral 160^0 arcs on the same pelvic cross section, field 10 x 10 cm^2, axes separated by 10 cm.

An example of a full data set for one beam, consisting of a depth dose curve and five equidistant cross beam profiles, is seen in Figure 1.
A measured isodose chart as shown in Figure 2 is also provided. Figure 2 also demonstrates the way in which a beam data check is performed. The recalculated isodose chart is superimposed over the measured one and differences may be noticed at once.

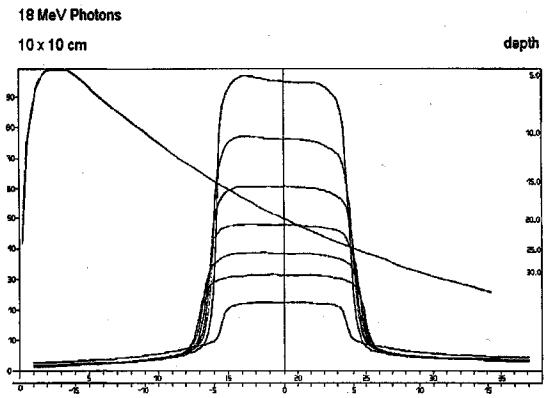


Fig.1
Example of basic beam profile data for a 16 MV photon beam consisting of a depth dose curve and seven equidistant cross beam profiles (not yet made symmetric) taken at the depths indicated at the right side.

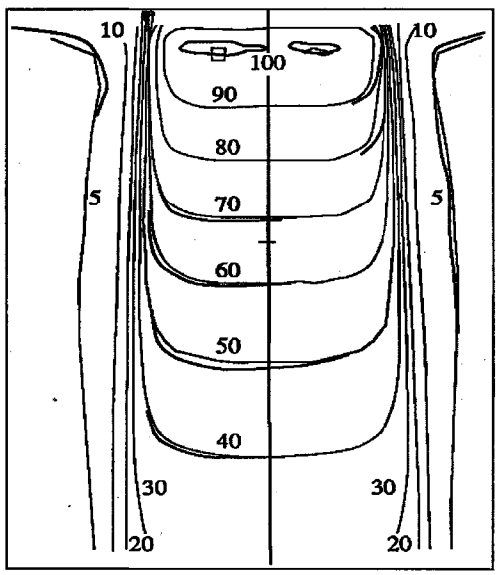


Fig.2
QA check of a 10 x10 field of 6 MV Comparison of calculated (thin) and measured (bold) single beam isodose lines.

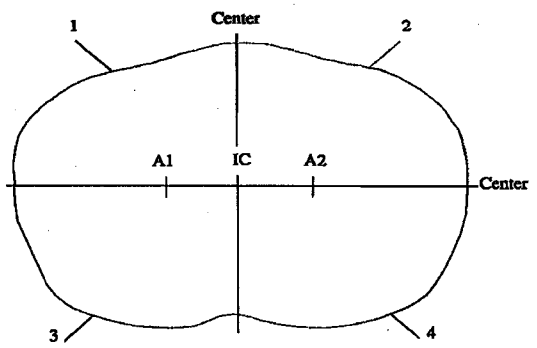


Fig.3
Homogeneous body cross section provided in natural scale with beam position 1 - 4 for a four beam isocentric (IC) technique, axes A1 and A2 for two lateral 160^0 arcs, and vertical and horizontal center lines to be used as test profile lines.

Figure 3 shows a homogeneous patient cross section added to the documentation of the Library. It is taken from an Rando Phantom and depicts a female pelvis in which a central isocenter is marked for a four field cross-fire treatment plan with equal field weights at isocenter. In addition, there are two lateral isocenters for two lateral arcs thought as additional teletherapy for an intrauterine afterloading application. The best-knowledge dose distribution for the four field technique based on the cross section of Figure 3 is derived with the treatment planning systems which performed best in the checks for reproducing the basic beam data. In addition, the calculation result was checked manually in terms of dose to isocenter and dose to single field dose maximum. Measurements for confirmation of calculated dose distributions were generally discarded because of the experimental uncertainty being larger than the uncertainties introduced by the physical model and algorithm on which the calculations are based.

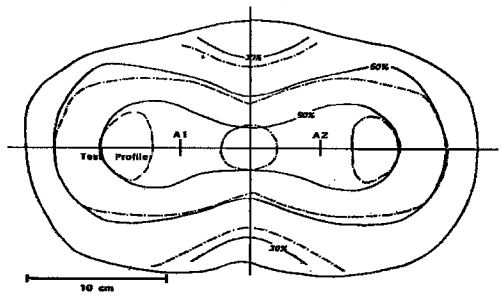


Fig.4
Bi-lateral arc dose distribution in the cross section of Fig.3 Solid lines represent „best-knowledge", broken lines a calculation result of a specific treatment planning system with identical beam data reflecting slightly different performance.

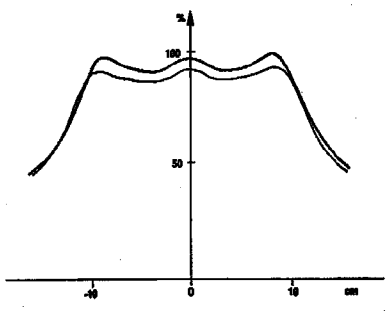


Fig.5
Test profile dose distribution along horizontal profile in Fig.3 for the two dose distributions in Fig.4 the bold curve representing the „best-knowledge" distribution.

The Library treatment plans are run from scratch for each check. Check result evaluation is basically done by superimposing the freshly calculated isodose distributions on the originally generated best-knowledge plan of the Library. Again differences are perceived easily qualitatively. However they are frequently difficult to express in quantitative terms. Therefore, dose distributions in "Test-Lines", i.e. profiles along lines representative for the dose distribution or critical to system performance, are also included. Figure 5 gives an example from early work in quality assurance in treatment planning systems (Rosenow, 1978).

Table II
The in-house test cases. Cases marked „sto" and "scr" are run from stored plan data or from scratch, respectively. Data marked* represent the regular constancy check.

1. Single photon fields (sto)	
1.1	Open fields
	- 90 cm SSD, 100 cm SAD, vertical on water phantom, all fields of all machines for which data are stored (sto: 10 x 10 for one energy per machine)
	- 100 cm SSD and 100 cm SAD, vertical on water, field 10 x 10*
1.2	Wedged field, 60 degree wedge
	- 90 cm SSD, 100 cm SAD, vertical on water phantom, field size 10 x 10*.
1.3	Off-axis calculation
	- 90 cm SSD, 100 cm SAD, vertical on water phantom, field 30 x 30, off0set plane at z = 0,14 and 15 cm
1.4	Half-blocked field
	- 90 cm SSD, 100 cm SAD, vertical on water phantom, field 20 x 20, half- blocked, and
	- two matching fields 10 x 20, appropriately weighted to simulate above half-blocked field
1.5	Inhomogeneity (lung)
	- 90 cm SSD, 100 cm SAD, vertical on water phantom, half-field rectangular lung inhomogeneity
2. Multiple photon fields and arcs	
2.1	Parallel-opposed fields
	- 90 cm SSD, 100 cm SAD, 20 cm thick water phantom, two fields of 20 x 20
2.2	Matching fields
	- two pairs of mahtcing parallel-opposed fields of 10 x 20, otherwise as in 2.1
2.3	360 degree arc
	- 100 cm SAD, circular phantom of 20 cm diameter, field 10 x 10, 360 degree rotation
3. Clinical cases, photons (scr,* alternating)	
3.1	Breast tangentials
3.2	Three-field three-plane oesophagus technique
3.3	Double-arc bladder plan
4. Brachytherapy	
4.1	Single Ir-192 and single I-125 seed (sto*, alternating)
4.2	String or 5 Ir-192 seeds
4.3	Gynecological implant with Fletcher-Suit colpostate (scr, * alternating with 4.4)
4.4	Brain implant (scr, * alternating with 4.3)
5. Electron fields	
5.1	All single fields of all machines for which data are stored (sto, * 10x10 for one energy per machine)
5.2	Two matched fields on a patients chest wall cross-section (scr)
6. Others	
6.1	CT scan on magnetic tape read into system and auto-contoured (scr. *)
6.2	Triangular cross-section to be digitized and plotted (scr, *)

II. Local QA Protocol

For the in-house tests according to above categories 2 - 4 local QA protocol should cover all dosimetry data entered into the system, some tests for basic performance characteristic of the underlying physical models and algorithms, and a small collection of typical techniques applied in the clinic. A listing of test cases which have been compiled for a specific radiotherapy department is contained in Table II.
A subset of these data marked with an asterisk (*) is used for the constancy checks. Since it is sufficient for beam or nuclide data and some other basic data to check their correctnes the according test cases are run with the stored beam data. These are marked "sto" in Tab. II. It is recommended to run these cases automatically by means of a special computer program. For other test cases which check the global performance on the system, or the total planning procedure, it is essential to run them from scratch. They are marked "scr" in Tab.II.

Figure 2 is also an example of a check outcome of a single stored beam. The following Figures illustrate the futher use of such an in-house QA protocol.

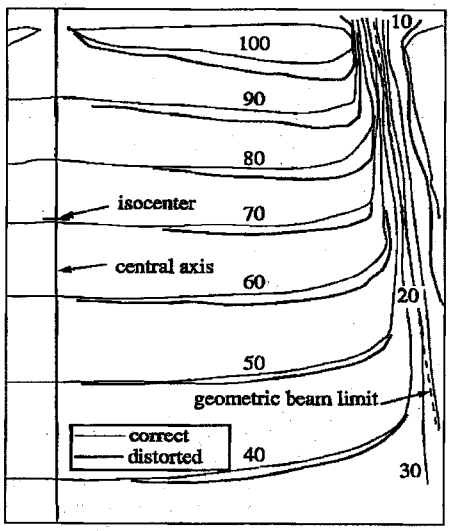


Fig.6
Beam data checkpointing to a data problem in the shoulder region of the cross beam profiles. Analysis revealed an erroneous assignment of 30 x 30 cross beam data to the nominal 40 x 40 beam.

Figure 6 shows the revelation of a serious problem in the data which would not easily have been detected in a regular treatment plan. During loading of beam data into the system cross beam profile data of a 30x30 cm^2 beam had by mistake been stored under the label of 40x40 cm^2 beam. The error in the shoulder region is up to 5% of the maximum dose.

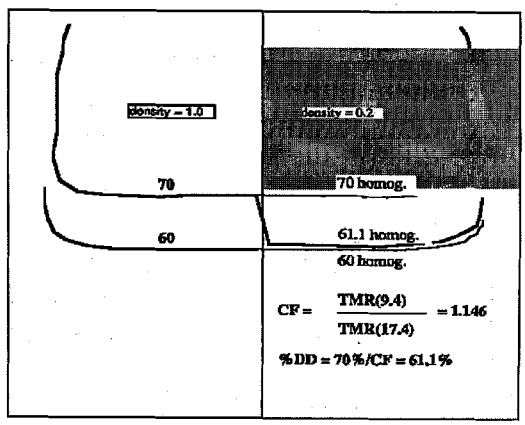
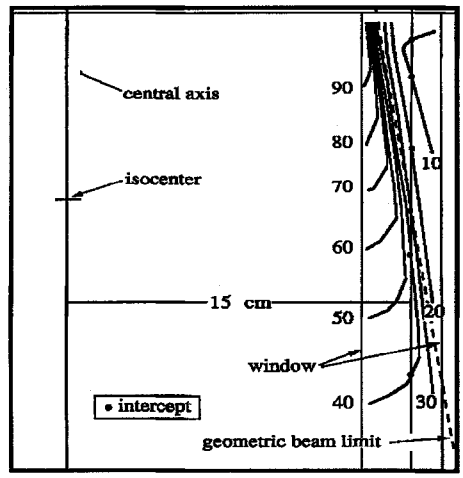


Fig.7
Test for algorithm for the calculation of inhomogeneities. The isodose shift and the stepwise change of the isodose line a simple effective depth scaling by means of the TMR ratio.

The Figure 7 test case allows for a simple check of the algorithm used for the calculation of tissue inhomogeneities. Here a lung is simulated and it is shown that the algorithm is based on an along-the-ray dose correction factor taking into account the ratio of TMR's for the real and effective depth.



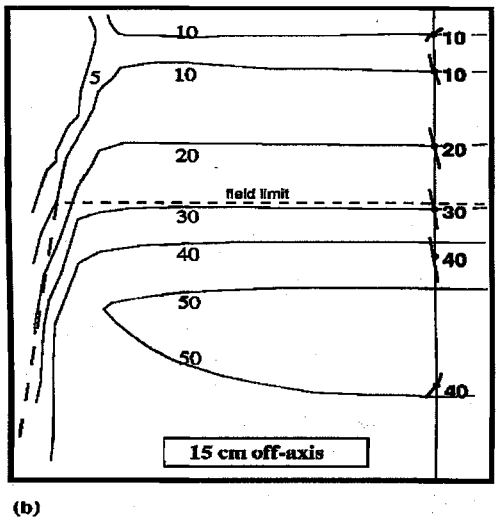


Fig. 8
Simple test for the accuracy od off-axis calculations in a 30 x 30 cm field. The isodose distribution in a vertical testline through the penumbral region at 15 cm from the centra axis (a) should ideally be exactly reproduced in the center line of the calculation plane 15 cm off-axis (b). In this case a difference of up to about 10% is seen in the lower part of the off-axis plane.

A straight-forward but effective check of the capability to calculate correct doses off-axis is demonstrated in Figure 8. If the model works correctly the dose in test lines parallel to the central axis at a distance of half the nomonal beam width in both main field axes should be the same. Therefore, the dose in the line 15 cm from the central axis in Fig. 8 (a) should be reproduced in the central line in the off-axis plane at 15 cm from the center plane (Fig. 8 (b)). In this example one finds discrepancies indicating an incorrect algorithm.

A half-blocked beam test calculation is shown in Figure 9 for successive releases of a planning system software. The improvement from an unacceptable to a realistic result is obvious.

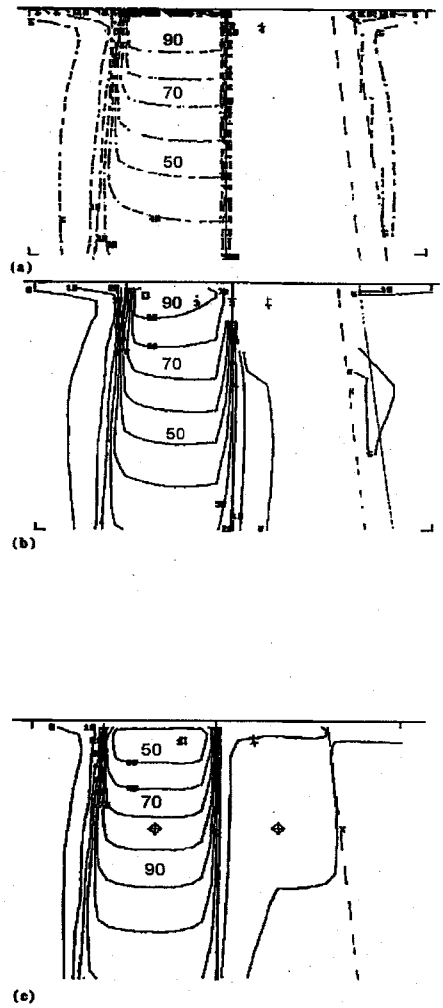


Fig. 9
Test for a half-blocked beam (a), (b) and (c) demonstrate increasing improvements of the algorithm of a certain treatment planning system. (a) Crude cut-out of the right beam by a block with 5% transmission resulting in a 5% isodose level at any location in the shadow region. Isodoses outside block shadow remain unchanged. (b) Slightly improved transition from open to blocked part of beam. (c) Inclusion of two-dimensional scatter distribution resulting in more realistic distribution.

CONCLUSIONS

Two different approaches to quality control of treatment planning systems have been proposed. The first one, Beam Data and Plan Library,

encompasses an extremely limited set of test cases. These consist of a few carefully selected beam data and some simple clinical treatment techniques.

The Beam Data and Treatment Plan developed by a task group of the German Society for Medical Physics is presented. It may be used (1) to check basic characteristics, accuracy and reliability of a local treatment planning system, and (2) to campare different treatment planning systems. Therefore, it is especially suited for pre-acquisition checks. The inclusion of treatment plans corresponds to recommendations of ICRU Report 42 (ICRU, 1987; DIN) and requirements of the German radiation safety rules ((DIN 6814). Such plans allow for an overall performance check of the planning system.

The Library should also be valuable for manufacturers. They may easily enter the beam data into their systems and thus allow any potential user to run the tests including the test treatment plans. This Library does not provide quality control of the local data. The user should be aware that he needs to verify the correctness of all input data of his system, e.g. by calculation of beam dose distributions and comparison to the original measurements.

For this purpose a quality control protocol for the local in-house checks is also presented. Feasibility of the checks in a busy clinical environment was one of the main design criteria. Hence the limitation to basic tests. More sophisticated tests, as, for example for three-dimensional consideration of inhomogeneities or for conformal and other specialized techniques were not intended. They need additional check protocols.

No tests of calculation results againts measurements other than directly entered into the system have been included. Therefore, any deviations or inaccuracies found are attributable to system performance only. The protocol allows to check the basic data, to derive at a closer insight in the behaviour of the underlying physical models, and to test the overall system performance in typical patient plans in external beam therapy with photons and electrons and with intracavitary and interstitial brachytherapy. Special cases of sufficiently general interest may be collected and added to the test case library whenever they arise.

The routine application of this in-house quality control protocol in a given clinical environment has enabled us to detect flaws of possible clinical relevance in our beam data files which might otherwise have remained unobserved.

The protocol also allows for a basic insight into the system limitations arising from the physical models and computational algorithms on which the system is built.

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