4 Measurement and Analysis

4.1 Overview and Underlying Principles

4.1.1 Introductory Remarks

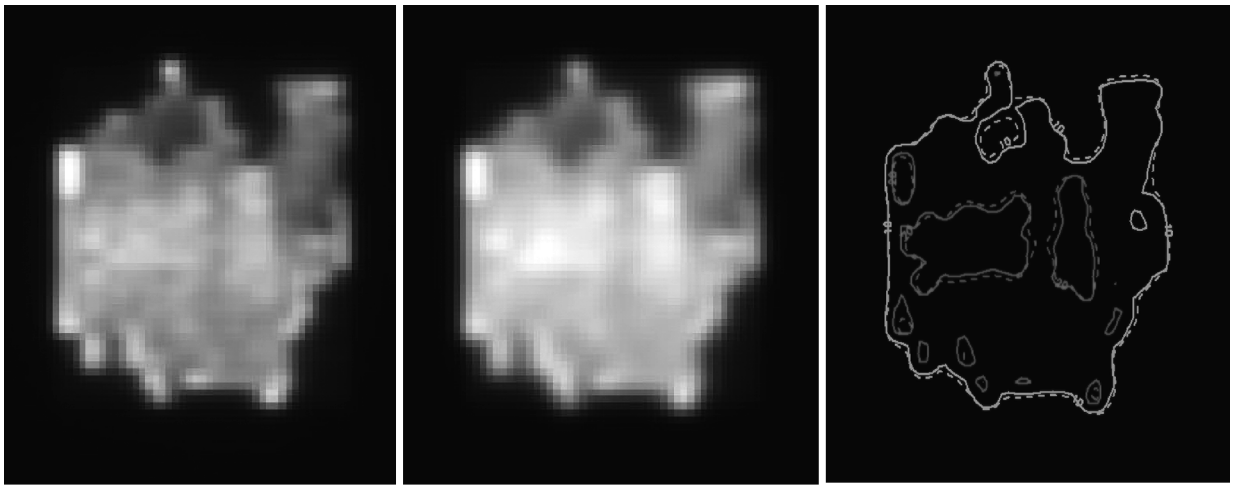
The physics and setup for film dosimetry have been described in the previous chapters. The measurement setup for IMRT dosimetry includes a traditional setup where the dose distribution in a plane perpendicular to the central axis is measured. This setup is suitable for verifying not only the tracks of MLCs delivering an intended fluence pattern across the beam but also the dosimetric accuracy of the delivery at a certain depth. Another setup that places film in parallel with the composite beams offers dose conformity verification only. The film overresponse in a perpendicular plane results from the low-energy scattered photons abundant at outside-penumbra regions of IMRT beamlets and, to a lesser extent, the radial variation of a photon spectrum (i.e., beam softening). The overresponse in a parallel plane has an additional contribution from the depth-dependent change in the proportion of the low-energy scattered photons due to in-phantom scattering. Therefore, rigorous interpretation of the IMRT dose distribution achieved by film dosimetry requires understanding the complicated nature of the film overresponse. For this reason, a relevant discussion and a rigorous investigation are presented in chapter 5.

Once the issues just discussed are properly understood, film dosimetry can be executed to verify a planned dose delivery to a patient via an accurate comparison of the measured dose distribution with the calculated distribution. The comparison involves the qualitative and quantitative evaluation of a discrepancy in the two distributions. The qualitative evaluation may be fast and easy, but it relies heavily on the experience of a physicist and/or a dosimetrist. The quantitative assessment can offer quantities for a more objective and straightforward decision as to the acceptability of the planned dose delivery, given that a supporting software tool is available. Because each evaluation method provides limited information, two or more evaluation methods are selectively used in actual practice. *To establish consistency and clinical relevance of evaluation, reference evaluation quantities and their acceptance criteria have to be determined institutionally*.

4.1.2 Superposition of Dose Distributions

Isodose Contours

The degree of agreement can be shown by overlaying the isodose contours from the measurement and the calculation in terms of selected dose levels, as shown in Figure 4.1. Although the overlay provides information along the isodose contour only, this method is useful for visually evaluating the compared dose distributions and identifying localized dose differences in the regions where hot or cold spots occur. If a relative dose comparison is the method of analysis, it is desired to select a reference or normalization point in a flat-dose region within a target.



(A) (B) (C)

Figure 4.1. Comparison of isodose contours (C) from film measurement (A) and RTP calculation (B). A dashed line is for the RTP calculation.

Dose Profiles

If the superposition of isodose contours shows local disagreement in the region of interest (ROI), then the superposition of dose profiles can be acquired along a line passing through the area of the disagreement. Typically, the ROI is an area where hot or cold spots occur within a target or critical organs. For an IMRT field, the line should be carefully selected to avoid the interleaf gap of the MLCs, which can potentially deliver a dose with a sharp gradient. This selection can be successfully done by locating the line (in parallel with the line of MLC travel) at some distance, across the line of MLC travel, from MLC leakage marks made outside the field. Figure 4.2 shows a typical example of dose profile comparison for an IMRT field.

4.1.3 Dose Difference Analysis

Dose Difference Image

While the preceding two methods allow limited two-dimensional or one-dimensional evaluation, a dose difference distribution, as shown in Figure 4.3, provides the discrepancy between the measured and calculated distributions two-dimensionally in terms of pixels. The difference image is obtained by digitally subtracting one from the other and can be visualized with gray image contrast or colors. As one of the main advantages of this analysis, the image offers quick and rough qualitative evaluation. In the example dose difference image in Figure 4.3, bright and dark pixels appear at the edges of a field because of the high dose gradient and the limitation of alignment in the region, less contributed by the systematic (or true) dose difference between the measurement and the calculation. Either absolute dose difference or percent dose difference can be optionally chosen by the user.

Dose Difference Distribution/Histogram

The dose difference image can be utilized for further quantitative analysis in terms of a dose difference distribution that provides additional information regarding the average dose difference and the standard deviation of a dose difference distribution, as shown in Figure 4.4. In case of two identical dose distributions, the dose difference distribution is presented as a delta function at zero. Under the Gaussian model (Tsai et al. 1998), the placement of the center of the distribution at some distance from zero is due to a systematic error that corresponds to the average dose difference between the measured and calculated distributions. Under the ideal condition, this difference is caused by potential errors in the delivery of planned beams caused by the limited reproducibility of an MLC position and motion and an output fluctuation from calibration. In reality, the difference is contaminated by additional sources of

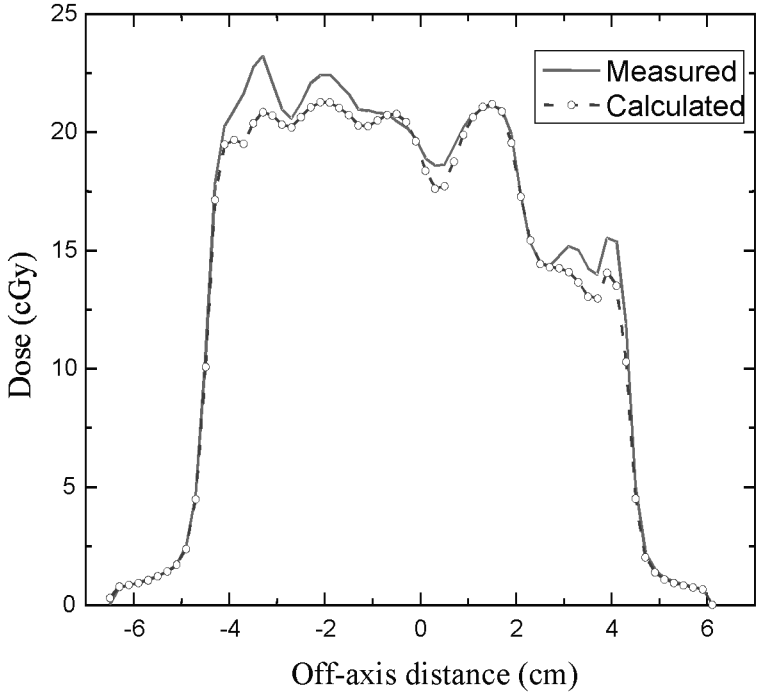


Figure 4.2. Superposition of dose profiles. The film shows overresponse throughout the infield region.

systematic and random errors. As discussed in the previous chapters and throughout this book, there is a film inaccuracy contribution because of the film overresponse and a contribution due to film response uncertainty. In addition, there is a contribution due to uncertainty in measurement setup. The RTP of concern has a limited capability to model radiation beams accurately. Therefore, the measured difference between the film measurement and the RTP calculation is contaminated by the aforementioned sources of errors together with a potential misalignment between the two distributions. Except for the film uncertainty, the other factors can occur systematically and thus have an effect on the average difference.

The preceding sources of a systematic error are apparent. For example, in Figure 4.4 the relatively large amount of the difference at both ends of the horizontal axis is likely to be associated with the pixels in the regions of a high dose gradient, including the overall field penumbrae, the regions where film overresponse is relatively high (the bars in the negative side of the axis only), or both. Therefore, the width of the distribution can increase as the degree of intensity modulation increases, which, in turn, increases the proportion of the regions that contain high dose gradients and/or local minima where film overresponse is relatively high. With a good choice and commissioning of an RTP, the beam modeling can be enhanced. The film uncertainty is as small as 0.5% to 0.6% (see chapters 3 and 7). The inaccuracy of film and RTP responses can be

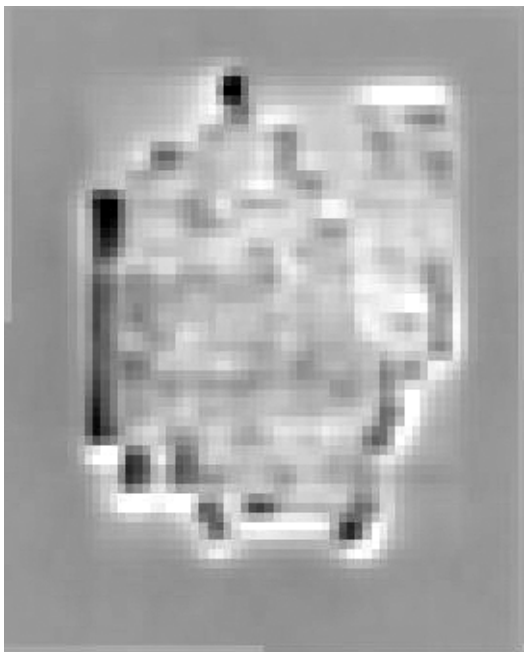


Figure 4.3. Dose difference image in gray scale.

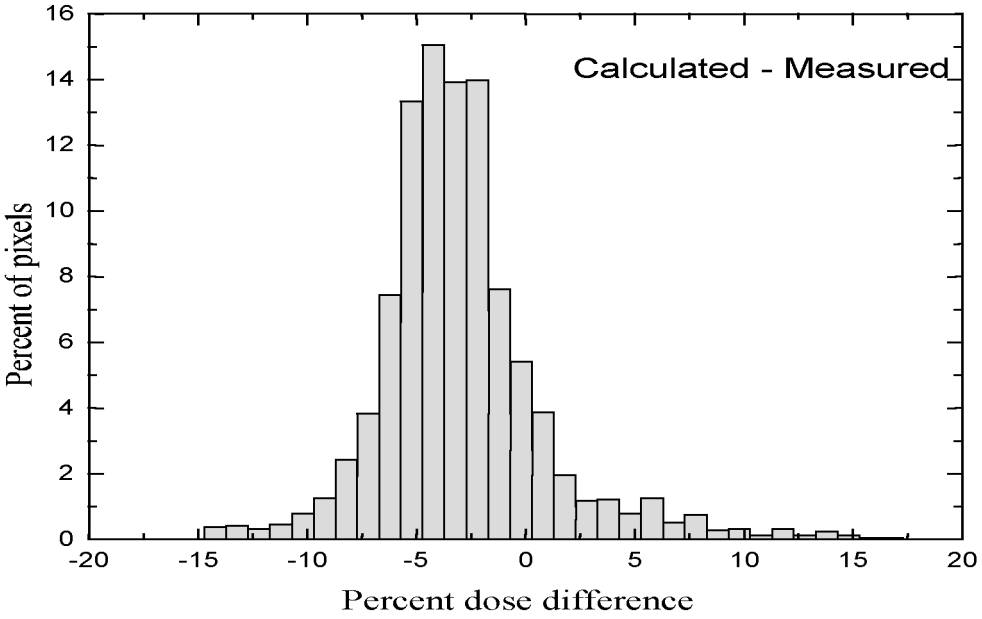


Figure 4.4. Dose difference histogram. Assuming the Gaussian distribution, the distribution has a peak at an average value of the distribution. On average, the measured distribution by film overresponds by about 4%, with an uncertainty given by the standard deviation of the distribution (i.e., $\sigma = \sqrt{(x_{av})} \cong 2$, where x_{av} is the average difference).

quantified in chapters 5 and 7. Finally, with good alignment, the contribution of misalignment, particularly in the region of a high dose gradient, to the dose difference histogram can be reduced. Then the dose difference histogram based on a dose difference image becomes a powerful tool, allowing a quantitative evaluation of the dose difference.

Dose Difference and Distance to Agreement Analysis

There exist other methods of analysis that account for the limitation of alignment. Van Dyk et al. (1993) introduced the idea of dividing the evaluation into two groups depending on the magnitude of dose gradient: high- and low-gradient regions each with a different acceptance criterion. The idea is based on the fact that dose difference in a high-dose-gradient region can be extremely higher than that in a lower-dose-gradient region because of imperfect alignment. This approach may provide exceedingly simplistic analysis for an IMRT field, where a diverse degree of a dose gradient typically exists.

To overcome this limitation, therefore, the simultaneous use of a distance-to-agreement (DTA) and a percent dose difference (DD) is proposed. These parameters can help evaluate the agreement of the two distributions in terms of misalignment and difference, respectively. DTA is defined as the nearest distance from a point of a reference dose to the point of the same amount of dose on the compared (or quarried) dose distribution. If the former is selected in the measured distribution, then select the latter in the calculated distribution. DTA, thus, is an indicator of how good the alignment of the two distributions is, provided that the difference is zero. The percent dose difference is defined as the difference in percent, implicitly assuming that the alignment of the two distributions is perfect. In reality, as the dose difference as well as the misalignment contribute to the difference of the two clinical distributions, use of the two independent parameters together will be necessary. By providing an acceptance criterion, respectively for a dose difference and a DTA, the acceptability of the comparison can be determined.

As an illustration of the foregoing considerations, Figure 4.5 shows an example of DD and DTA analyses where 65% and 75% of the data points satisfied the acceptance criteria of DD and DTA, respectively. The figure shows the systematic dose difference as well as misalignment. The placement of data points in the area of a relatively high DTA is more likely to be due to the contribution from the region of a relatively low dose gradient in the dose distribution than that from the area of a relatively

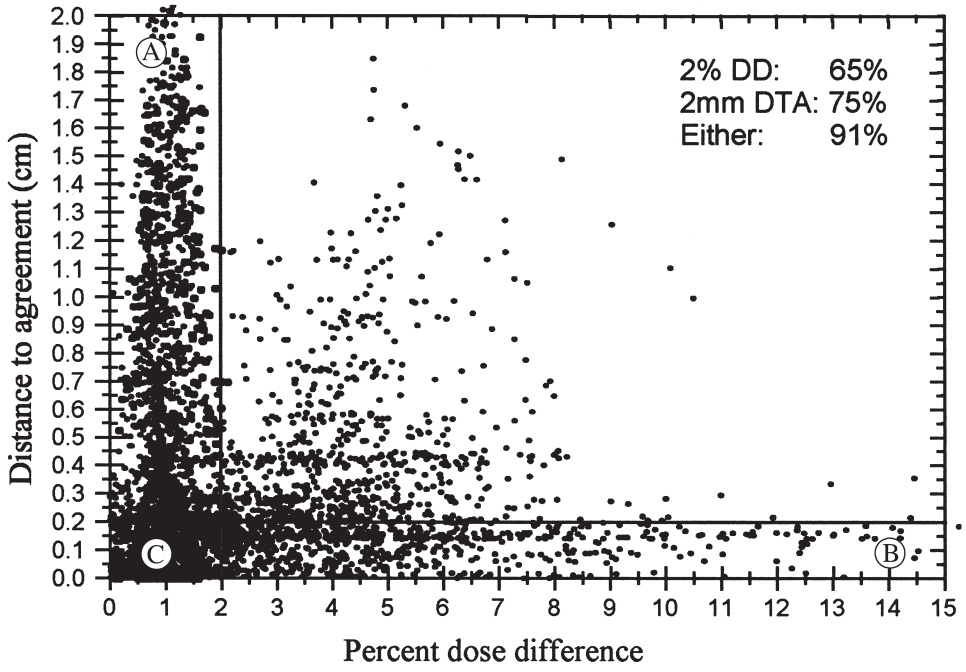


Figure 4.5. Dose difference and distance-to-agreement analysis. Each data point is associated with a DTA and a DD. Ninety-one percent of test points passed either 2% DD or 2 mm DTA criteria.

high dose gradient, because in the region of a low dose gradient even a small amount of dose difference, not to mention a large difference, in the two distributions can potentially lead to a relatively high DTA to a neighboring point in the compared distribution. Therefore, the points in the area of a high DTA and a low DD (see A in Figure 4.5) have high probabilities of having originated from the region of a relatively low dose gradient; the acceptability of their DD analysis indicates that the two distributions are in good agreement in terms of the DD, in spite of their high DTAs in the region of concern. On the contrary, data points occurring in an area of relatively low DTA are more likely to have been contributed from the region of a relatively high dose gradient in the dose distribution than from an area of a relatively low dose gradient. This is because in the region of a high dose gradient even a relatively large amount of dose difference, not to mention a small amount of dose difference, in the two distributions can result from a little misalignment. Therefore, the points in the area of a low DTA and a high DD (see B in Figure 4.5) have higher probabilities of origination from the region of a relatively high dose gradient, including the overall field penumbrae, than from the region of a relatively low dose gradient. The points in the region of a low DTA and a low DD (see C in Figure 4.5) can be contributed from various regions where the agreement between the two distributions of comparison is good in terms of both alignment and difference (within 2 mm DTA and 2% DD, respectively). It is in the user's discretion to assign clinically relevant values to the acceptance criteria of DTA and DD.

Gamma Analysis

Although the use of the two factors provides the independent evaluation of a dose difference and misalignment, the gamma offers a composite analysis with the two variables collapsed into one parameter (Harms et al. 1998; Low et al. 1998c; Dupuydt, Van Esch, and Huyskens 2002). The gamma is defined as the square root of a linear quadratic addition of the two factors, while they are provided in relative magnitude to their acceptance criteria (C_{DTA} and C_{DD}), as shown in equation (4.1).

$$\Gamma = \sqrt{\left(\frac{\text{DTA}}{C_{\text{DTA}}}\right)^2 + \left(\frac{\text{DD}}{C_{\text{DD}}}\right)^2} \qquad (4.1)$$

Gamma analysis thus compromises between the DD and the DTA. As a result, it becomes impossible to discriminate between the DD and the DTA for investigating the cause of the result (acceptance or not) of the comparison. For example, the gamma can still be lower than $\sqrt{2}$, even if one of the two parameters (say, DTA) is greater than its criterion (C_{DTA}), if the other (DD) is sufficiently smaller than its criterion (C_{DD}) to compensate for the excess of the former. Therefore, the gamma increases when the position of a data point is moved away, not only diagonally but also laterally and vertically, from the origin in Figure 4.5. For this reason, it becomes necessary to use one of the previous analyses as well, such as the superposed dose profiles. Such superposition can be acquired along a line passing through the suspicious regions assigned with high values of the gamma. The gamma analysis and the superposition of dose profiles are complementary to each other and thus become a useful set of dose comparison tools.

Figure 4.6 shows, for the criteria of 1% DD and 1 mm DTA, the region associated with gamma smaller than 1 and the other regions with gradually increasing values of gamma. In this figure, 99.1% of points pass the criteria of 1% DD and 1 mm DTA. In Figure 4.7, 99.6% of points pass the criteria of 2% DD and 2 mm DTA. It is at the user's discretion to assign clinically relevant values to C_{DTA}, C_{DD}, and the gamma.

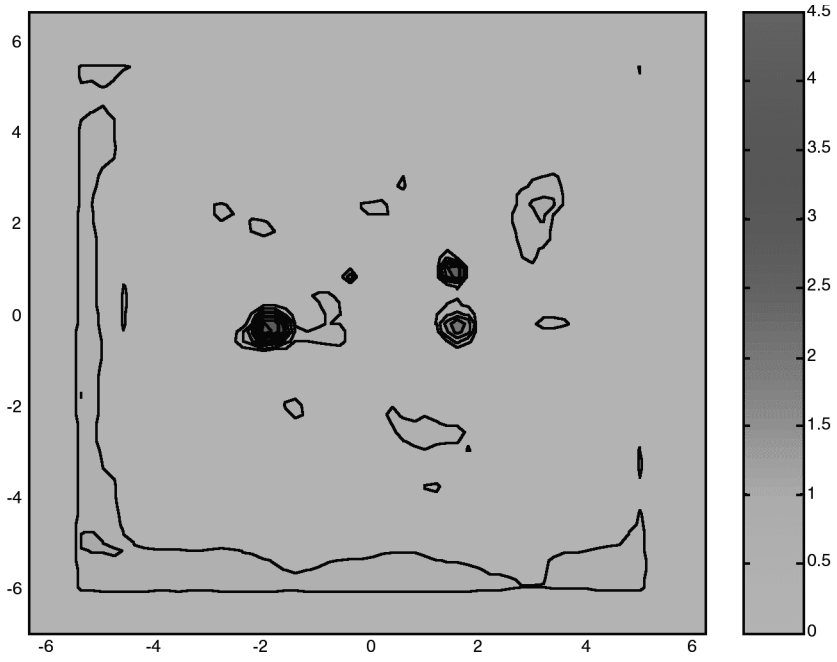


Figure 4.6. Gamma test with 1 mm DTA and 1% DD criteria.

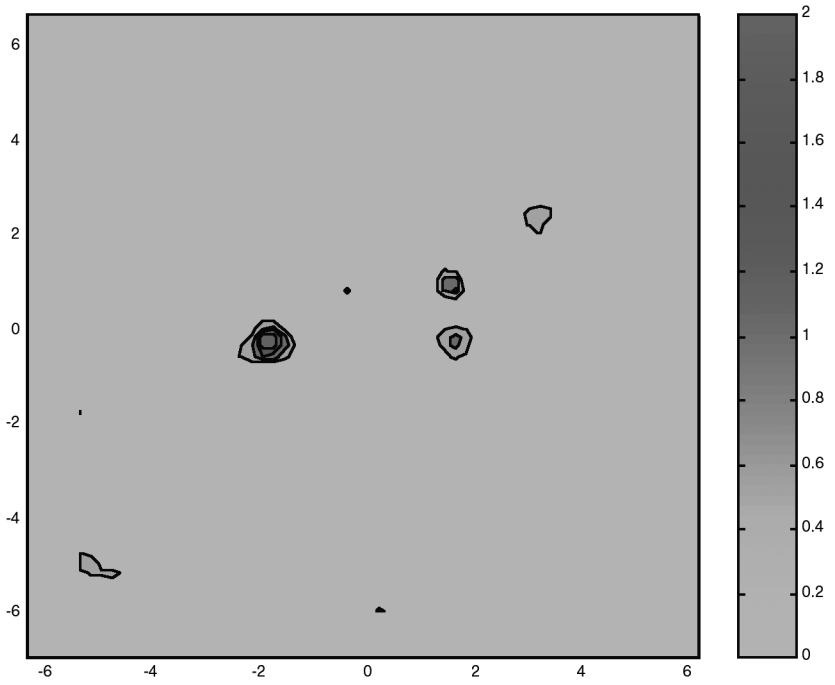


Figure 4.7. Gamma test with 2 mm DTA and 2% DD criteria.

4.2 Procedure

4.2.1 RTP Calculation

A. Construct a water-equivalent flat phantom with the size (see step D) and density closest to those for film measurement. *Depending on RTPs, the size of the phantom construction may be limited. This phantom size requirement is not as strict as that between film measurements (i.e., calibration and IMRT beam measurement) because the contribution of scattered photons to a calculated dose is not as significant as that to a measured dose by film.*

B. Irradiate the flat phantom at 100 cm SSD by each treatment field with the optimized beam parameters (i.e., weights or dose) and calculate dose distribution at 10 cm or other depth on a perpendicular plane to the beam axis and on a plane at 2.5 mm off-axis distance from the isocenter in parallel with the line of MLC travel (Y1 = 0 or X1 = 0 depending on the manufacturer of the linac). Give an extra margin of 10 cm for the calculation region from the edge of the field. If the RTP under consideration allows, prescribe the same number of MU used for the film exposure for each beam. If the RTP does not allow prescribing the number of MU, then normalize the calculated dose distribution by assigning a level of dose at some point in the distribution such as the dose maximum point or a point in a flat-dose region. *Ensure that the assigned number of MU or the dose does not exceed the recommended operational dose limit of the films: 40 cGy for XV and 200 cGy for EDR2 film (if necessary, as a maximum, 65 cGy can be used for XV film). Scale down the dose if necessary for film measurement. A finer calculation grid size is recommended, because it minimizes uncertainty due to data interpolation. The placement of the parallel plane at the above off-axis distance is to avoid measurement between MLCs and thus susceptibility to the potentially high dose gradient.*

C. Extract and transfer the distribution/image files in any desired format to a software tool in your center. Note down the treatment (i.e., measurement) parameters such as the number of MU and the patient number in Table 4.1, and transfer MLC sequence files for each treatment field to the treatment machine.

Table 4.1. IMRT Beam Parameters

Patient ID: Patient Name:

No.	MU	Remarks
1		
2		
3		
4		
5		
6		
7		
8		
9		

4.2.2 Film Measurement with a Perpendicular Setup (Continued from a Calibration Process)

The choice between parallel and perpendicular setups is at the user's discretion.

D. Warm up the linac selected for treatment. Place the solid-water phantom with a size of 30 cm × 30 cm × 30 cm or greater on top of the linac couch as shown in Figure 4.8. Ensure that the phantom is the same size, particularly the same backup thickness, as that used for calibration. Level the phantom by placing thin objects between the couch and one or more corners of the phantom. Set the SSD at 100 cm. Place the radiation beam centrally on top of the phantom by ensuring that the light field of the largest IMRT field is at least 5 cm inside the phantom edge. *Sometimes this requirement cannot be strictly met with a phantom size of 30 cm × 30 cm × 30 cm. Therefore, it is recommended to use a 40 cm × 40 cm × 40 cm phantom. A plastic phantom (i.e., polystyrene) may be used, but the solid-water phantom is recommended for comparison with RTP calculations in a water phantom.*

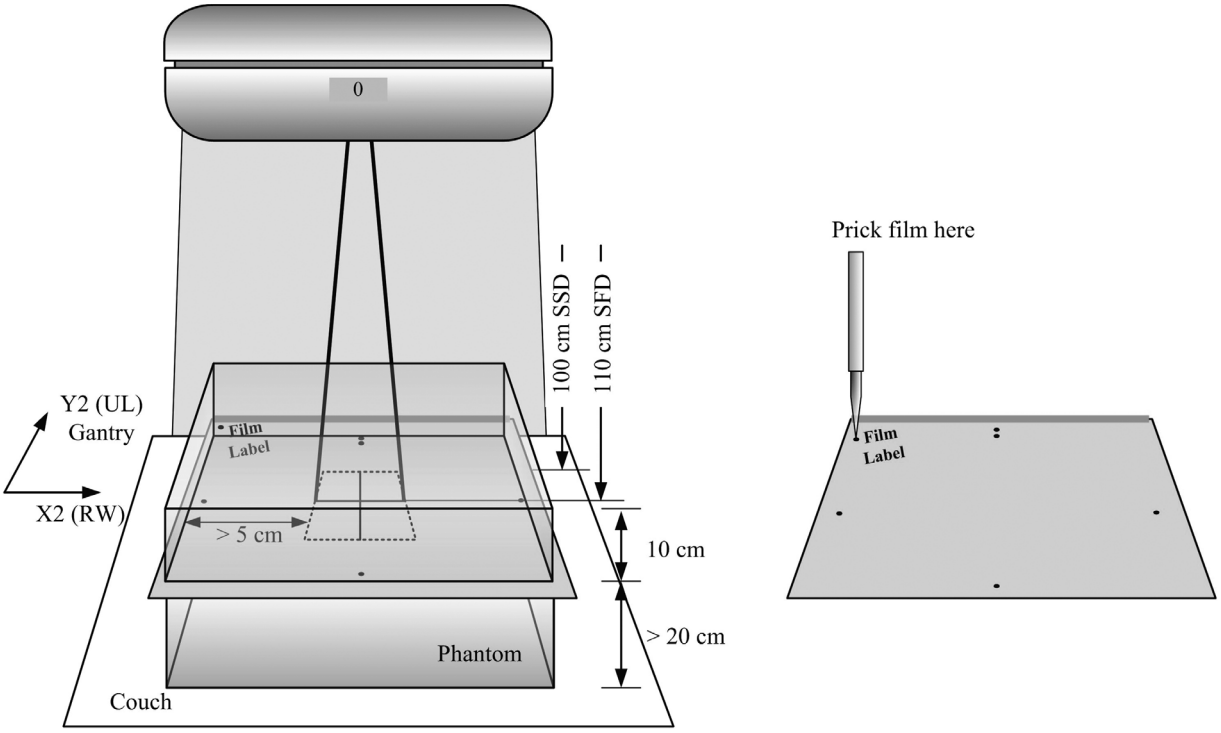


Figure 4.8. Detailed perpendicular phantom setup.

E. Take boxes of Kodak XV film with size 33 cm × 41 cm into the linac control area. Write the experimental conditions, including date, energy, SSD, depth of measurement, film orientation, field size, number of MU for irradiation, and field number on the film envelope. Prick a hole on the X1 and gantry side on the film. Place the film at 10 cm or other depth of the phantom with the hole in the corresponding location, as shown in Figure 4.8. Additionally, prick a few holes along the laser lines on the film envelope if necessary or required by your data processing software. Leave the room; do not leave the films in the room.

F. Bring in and program MLC files starting with the first treatment field and deliver the determined number of MU listed in Table 4.1. After preparing the new film according to step E, take a new film into the room

and exchange it with the exposed film. Lift only the top phantom blocks without moving the remaining phantom. Take the exposed film out of the room and irradiate the film with the next field. Repeat this procedure until the final treatment field.

4.2.3 Film Measurement with a Parallel Setup

G. Repeat steps D through F using the parallel setup with the gantry rotated at 270° (Figure 4.9). Level the phantom and align the beam axis to the film plane at 2.5 mm off axis, using the cross hair, the optical distance indicator, and/or the lateral laser. Use a compression box, if available, and set up accordingly with the gantry at 0° (Burch et al. 1997).

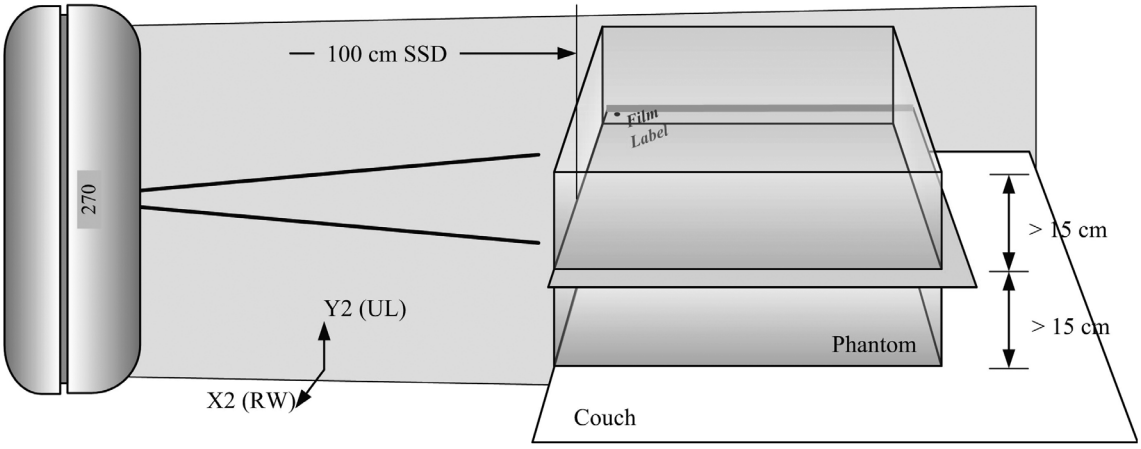


Figure 4.9. Detailed parallel phantom setup with gantry and collimator at 270°. Provide additional ±1° to reduce the potential effect of film orientation, if it exists in your setup.

4.2.4 Film and Data Processing

H. Warm up the film developer. Process at least two blank films for additional warmup. Tear down the film envelope and continuously process the assigned reproducibility check films, the calibration films, the measurement films of IMRT, and another set of reproducibility check films. After the films are dried, visually check whether the surface qualities of the processed films are fine and polished. Copy the experiment parameters from the film envelope to the pricked corner of the film away from the exposed region while the next film is in the processor. Sort the films and store in clean envelopes. Write the parameter summary on the envelopes.

I. After the film scanner is warmed up (i.e., 30 minutes), run the scanner with at least two blank films.

J. Extract and transfer the distribution/image files in any desired format to a data processing software tool in your center. Subtract background and convert the OD into dose by using the calibration curve previously obtained.

K. Overlay the film and the RTP dose distributions for each field of the parallel and perpendicular exposures using the pin marks, if necessary. Visually inspect the alignment between the two distributions and reduce potential misalignment. Between the two distributions, acquire the dose difference image (Figure 4.3) and see whether the alignment is satisfactory.

L. Set the institutional standard in terms of X, Y, and Z such that X% of data points fall below 2 (or 1)% in DD; Y% of data points fall below 2 (or 1) mm in DTA; Z% either criterion. Set the criterion of the average DD. Alternatively, or additionally, set the acceptance criterion of gamma (Figures 4.6 and 4.7) in terms of W%, so that W% of data points have passed the gamma test (i.e., gamma < 1) for 2 (or 1)% in DD and 2 (or 1) mm in DTA.

M. Between the two distributions, acquire the dose difference distribution (Figure 4.4) and the DTA and DD distributions (Figure 4.5). Calculate X, Y, and Z. Check whether the average DD and the DTA and DD distributions of all data points meet the institutional standards.

N. Alternatively or additionally, plot the gamma distribution between the two distributions. Calculate W. Check whether or not the gamma distribution of all data points meets the institutional standard.

O. Extract superposed linear scans along the lines passing through the regions of local failure for the gamma analysis.

P. Sample several points in the regions of a local maximum and minimum and a local failure. Fill in a copy of Table 4.2 with the amount. The value with + sign indicates an RTP dose greater than a film dose.

Q. Interpret the dosimetric meaning of the deviations in Table 4.2 considering the trend of the film overresponse, the RTP over/underresponse (from chapter 5), the film and setup uncertainty, and misalignment. Select the points at which the amount of the deviation exceeds more than several percent, set by the institutional standard.

R. Report the results of X, Y, Z, W, and the average DD with a standard deviation. Additionally report the points of failure (from step Q) and their clinical and anatomical relevance.

Table 4.2. Deviation of the RTP Dose Distribution from the Film Dose Distribution

Patient name: Patient ID No.: Date:

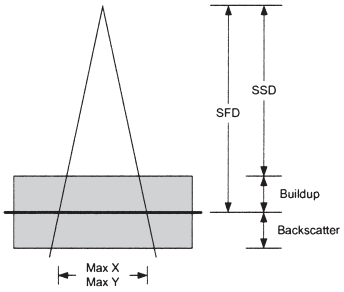
Energy: MV SSD: cm

Depth of measurement: cm

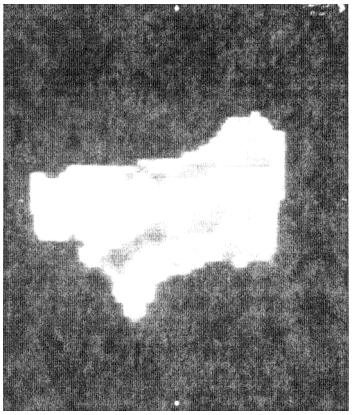
Points/Field Number	1	2	3	4	5	6	7	8	9
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									

Appendix: Film Dosimetry Order Form

Date: / /

IMRT Pre-treatment Film Measurement								Remarks
Patient Name			**Record No.**					
Plan Name			**Accelerator**					
Tx Start Date	( )fr		**Due Date**	( )fr				
Tumor Site	☐ HN ☐ Breast ☐ Prostate ☐ Brain ☐ Lung ☐ Pelvis ☐ Abdomen ☐ GYN ☐ Other( )							
MLC File	Beam Name		Max Dose	IMRT	Split	Coll Ang	Gant Ang	Dose Scale
	1							☐0.5 ☐2 ☐3
	2							☐0.5 ☐2 ☐3
	3							☐0.5 ☐2 ☐3
	4							☐0.5 ☐2 ☐3
	5							☐0.5 ☐2 ☐3
	6							☐0.5 ☐2 ☐3
	7							☐0.5 ☐2 ☐3
	8							☐0.5 ☐2 ☐3
	9							☐0.5 ☐2 ☐3
Film	☐ XV-2 Small ☐ XV-2 Large ☐ EDR Small ☐ EDR Large							
Energy	☐ 6 MV ☐ 18 MV ☐ Mixed							
Flat Phantom	Material	☐ Water Equiv. Plastic ☐ Special ( )						
	Thickness	Buildup Backscatter	cm cm					
	Setup	SSD SFD	cm cm					
Film Calibration	☐ 10 x 10 cm^2 ☐ Special ( )							
	☐00 ☐05 ☐10 ☐15 ☐20 ☐25 ☐30 ☐35 ☐40 ☐45 ☐50 ☐60 ☐70 ☐00 ☐05 ☐10 ☐20 ☐50 ☐100 ☐150 ☐200 ☐250 MU							

Labeling and Pricks



On cross-hair:
☐ 4 Pricks
☐ Double Exposure

Patient ID:
☐ Upper right gantry
☐ Upper left gantry

Field ID:
☐ Upper right gantry
☐ Upper left gantry

Energy ID:
☐ Upper right gantry
☐ Upper left gantry

Label Information
☐ Measurement Date
☐ Patient Name or Record Number
☐ Plan Name
☐ Beam Name
☐ Given Dose/MU
☐ Beam Energy and Accelerator
☐ Setup
☐ Number of Repeats
☐ Film Type

e.g. 02-17-04 Patient
IMRT Beam1 1st
125 MU 6MV 21EX
95cm SSD Depth 5cm EDR2

Special Instructions:

Film Measurement Report			
Patient Name	*Last, First*	**Record No.**	*000001*
Plan Name	*IMRT Test*	**Accel**	*21EX 6MV*
Beam	*Beam03*	**Max Dose**	*28.34 (1/1)*

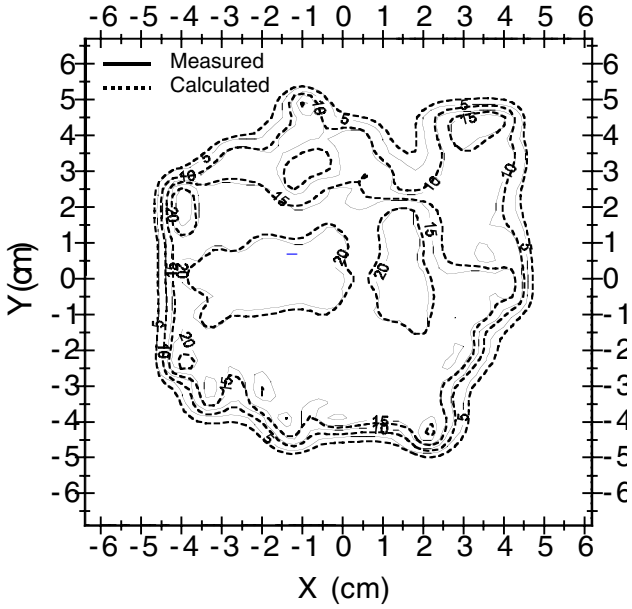
Date: / /

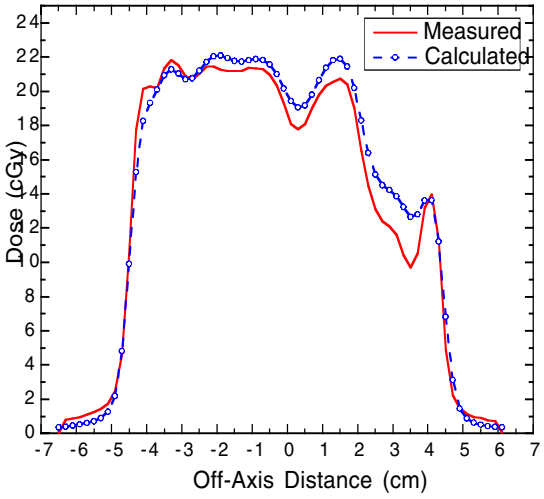
	①	②
Target Region	■ GTV ☐ CTV ☐ PTV	☐ GTV ☐ CTV ☐ PTV
Anatomical Region	Left Tonsillar Fossa	
Under/Overdose, relative to the prescribed dose	■ Underdose by _5_ % ■ Overdose by ___%	☐ Underdose by ___% ☐ Overdose by ___%
Causes of Under/Overdose	■ Misalignment ■ Film response error ☐ RTP error ☐ MLC leakage ☐ Interleaf shielding ☐	☐ Misalignment ☐ Film response error ☐ RTP error ☐ MLC leakage ☐ Interleaf shielding ☐
Exceed criterion ?	■ Yes ☐ No	☐ Yes ☐ No
Actions	■ Remeasure ☐ Carry out treatment ☐ Report the deviation to Doctor ☐ Replan ☐	☐ Remeasure ☐ Carry out treatment ☐ Report the deviation to Doctor ☐ Replan ☐
Remarks		

Dosimetrist: _____

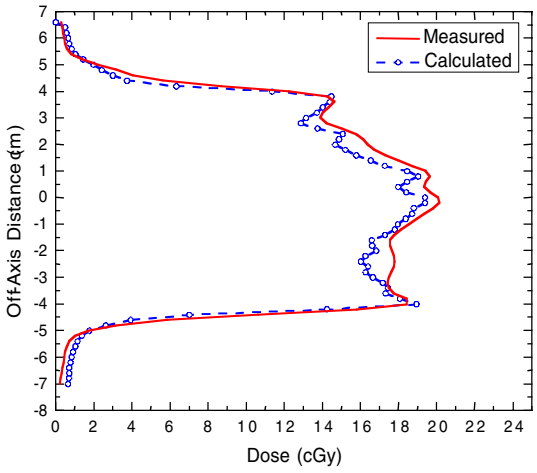
Physicist: _____

Film Measurement Report			
Patient Name	*Last, First*	**Record No.**	*000001*
Plan Name	*IMRT Test*	**Accel**	*21EX 6MV*
Beam	*Beam03*	**Max Dose**	*28.34* (*1/1*)

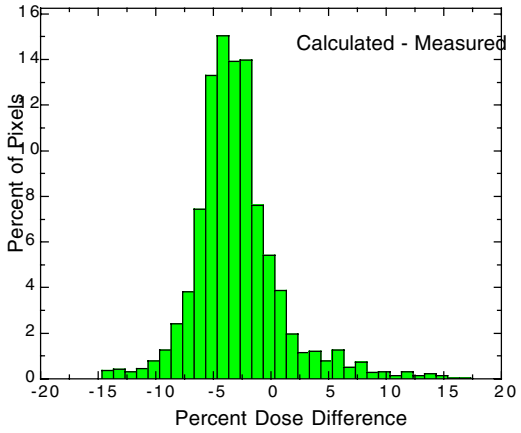




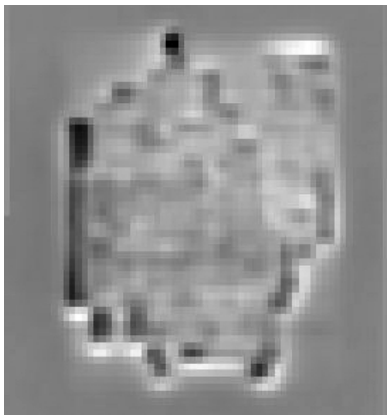
Dose profile at y=0.25 cm



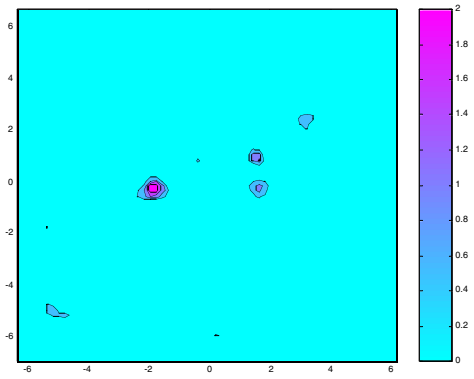
Dose profile at x=0.0 cm



Difference Histogram (Avg = -2.45)



(Calculated-Measured) images



Gamma Analysis (99.6% pass to 2% and 2mm)