Introduction

Brachytherapy treatment isodose plans are commonly used to determine the optimal source strength and distribution for the treatment to be delivered, to document the isodose distribution resulting from a delivered treatment, and to serve as a guide for subsequent management of a patient’s disease. While most brachytherapy treatment plans that a clinical medical physicist encounters on a routine basis serve the former two purposes, the use of brachytherapy treatment plans as a guidance for future patient treatment is equally important, especially in the cases of multifractionated brachytherapy treatments such as high dose-rate (HDR) intracavitary gynecological procedures; or in the case of post-permanent prostate implant dosimetry plans, where the quality of the implant is evaluated and used as guidance to determine the subsequent management of the patient’s disease, including potential re-implantation of the prostate to increase doses to the “cold-spots” of the initial implant. Accuracy of treatment plans therefore not only has direct impact on the delivery of an individual brachytherapy treatment, but also impacts on the entire process of the management of a patient’s disease. Institutional policies should be implemented that require physics review of all brachytherapy treatment plans, as well as the timing of the review relative to the start and/or completion of the treatment.
A physics treatment plan quality assurance (QA) review scrutinizes a brachytherapy treatment plan for the following end points:

1. Treatment plan’s adherence to institutional treatment policies and/or national treatment guidelines.
2. Accuracy of technical parameters.
3. Suitability of the plan for the patient’s treatment in terms of dose/source distribution optimization, dose homogeneity, target coverage, and critical organ doses.

In addition, an independent calculation is often performed to validate the correctness of the treatment. While this calculation may not be able to detect errors on the order of a few percent in the treatment plan, it serves to alert the physicist in the event that a significant error has occurred. Such errors can occur due to the entry of incorrect technical parameters, a misinterpretation of the treatment prescription, or a software bug that was not detected in the treatment planning system (TPS) acceptance testing and commissioning process.

Treatment plan QA review, by default, assumes that the TPS has been properly acceptance-tested/commissioned, that the source data are up-to-date, and that periodic TPS QA tests have been performed. However, TPS QA does not replace or in any manner diminish the importance of QA review of treatment plans, even for basic algorithmic accuracy or correctness. A state-of-the-art brachytherapy TPS is a complex software and hardware system, capable of electronic input and output data transfer; manipulation of volumetric patient data including image fusion, coordinate transform and rotation, and segmentation; automatic or semi-manual optimization of HDR dwell positions and times; and dose calculation using various formalisms. A typical TPS acceptance testing and commissioning process will not allow testing of all available functions in the TPS nor the different manners that these functions are combined to obtain a patient treatment plan. Vigilance and efforts in detecting any unexpected or abnormal TPS behavior are therefore a critical aspect of treatment plan QA review.

### Review of Treatment Prescription

While the preparation of a treatment prescription is the sole responsibility of the treating radiation oncologist, a careful review of the prescription is an integral part of any treatment plan QA review. Review of the prescription should aim at the following aspects:

1. Prescription is appropriate for the goals of the brachytherapy treatment. While a physicist cannot question every aspect of a treatment prescription, it is important that the physicist understand the goals of the treatment and how the prescription is designed to achieve these goals. Errors in prescription do occur, for example, due to a miscommunication between the departments of surgery, pathology, and radiation oncology, or simply in the process of transcribing information on patient disease or the prescription itself. A prescribed minimal peripheral dose of 145 Gy for the treatment of permanent prostate seed implant, for example, using $^{125}$I seeds, is only appropriate if the patient is to receive brachytherapy alone for his early stage prostate cancer. Variations in prescribed dose or isotope should be immediately brought to the attention of the treating physician. Review of the treatment prescription therefore necessitates a careful reading of the patient’s history and physical exam report, including the stage of the disease, as well as any previous treatment that the patient may have received.

2. Prescription adheres to institutional treatment policies and/or national treatment guidelines for the disease. Many institutions have treatment policies or protocols that aim to maintain consistent treatment prescriptions and techniques for patients with similar diseases. In addition, national organizations, such as the American Brachytherapy Society, have published guidelines and pattern
of care studies on the brachytherapy treatment of various cancers (Arthur et al. 2003a; Beyer et al. 2000; Gaspar et al. 1997; Nag 2000; Nag et al. 1993; 1999a,b; 2000a,b,c; 2001a,b,c; 2002; 2003a,b; Potter et al. 2001). These guidelines, in the event that no institutional treatment policies exist, should, in general, be followed. Random deviations from an existing protocol not only endanger the success of a patient’s treatment, but also carry medical-legal consequences. While individual treating physicians may choose to deviate from these protocols based on the particular patient’s disease and physical conditions, the physicist should communicate with the treating physician to assure such deviations are reasonable to the extent that that patient’s disease warrants. Frequent deviations in treatment prescription from institutional and/or national treatment guidelines should proceed either in a clinical trial setting, or should lead to a discussion on the need to revise treatment protocols. At Mallinckrodt Institute of Radiology, the treatment of cervical cancer follows a treatment protocol (see Table 1), using a combination of whole pelvis and split-field pelvis external beam fields, interlaced with brachytherapy tandem and ovoids intracavitary implants. The source-loading pattern for a given tandem and ovoid insertion also follows a strict protocol (Grigsby, Williamson, and Perez 1992). Physicists are expected to be familiar with these protocols and to review the prescriptions of a tandem and ovoids treatment for deviations.

When starting a new treatment site or technique for which no institutional protocols exist, the physicist should work with the treating physician to develop such a protocol, based on literature reviews and attendance at workshops and training courses. Examples of such treatments include accelerated partial breast brachytherapy treatments using low dose rate (LDR), interstitial HDR, or MammoSite® HDR techniques.

3. The prescription should be complete and accurate for fulfillment of regulatory requirements. The Nuclear Regulatory Commission (NRC), in Title 10, Part 35 of the Code of Federal Regulations, specifies the required information to be completed in the “written directive” before and/or after

### Table 1. Mallinckrodt Institute of Radiology Treatment Policy for Cervical Cancer

<table>
<thead>
<tr>
<th>Treatment scheme</th>
<th>Indication</th>
<th>External beam treatment (Gy)</th>
<th>Intracavitary treatment</th>
<th>Total: smallest to largest insertion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Whole pelvis</td>
<td>Split field</td>
<td>Maximum vaginal dose (Gy)</td>
</tr>
<tr>
<td>A</td>
<td>IB &lt; 2 cm</td>
<td>0 Gy</td>
<td>45 Gy</td>
<td>7000</td>
</tr>
<tr>
<td>B</td>
<td>IB 2–4 cm</td>
<td>10</td>
<td>40</td>
<td>7500</td>
</tr>
<tr>
<td>C</td>
<td>IB/IIA/IIIA bulky (&gt;4 cm), limited parametrial extension</td>
<td>20</td>
<td>30</td>
<td>8000</td>
</tr>
<tr>
<td>D</td>
<td>IIB/IIIB bulky, extensive parametrial extension</td>
<td>20</td>
<td>40</td>
<td>8000</td>
</tr>
<tr>
<td>E</td>
<td>IIB, IIIB, IV, poor anatomy, poor regression</td>
<td>40</td>
<td>20</td>
<td>6500</td>
</tr>
</tbody>
</table>

insertion of sources into the patient. While not inherently a part of a treatment plan review, it is often convenient for the physicist to review the prescription, if used as the written directive for the treatment, to ensure that all required information is entered correctly.

**Review of Technical Aspects of Treatment Plans**

A careful review of technical aspects of brachytherapy treatment plans typically constitutes the most time-consuming part of a comprehensive treatment plan QA review. It is also the part of a treatment plan QA review that requires the expertise of a qualified physicist. Once satisfied that the treatment prescription is appropriate for the treatment under review, the physicist can now concentrate on the treatment plan itself. This review should address all milestones in the process of treatment plan creation, starting from patient data acquisition, be they volumetric or planar images, to the adequacy of final isodose plots. A checklist is often helpful for review of complex treatment plans, especially for HDR treatments, where the plan review must be completed in a compressed timeframe.

**Patient Image Review**

A review of patient imaging serves multiple purposes in the process of treatment plan QA review. It assures that the applicator insertion is adequate for the treatment, that the images were acquired with minimal artifacts, and that the images are optimized for accurate source/applicator localization and dose calculation.

The very first step in patient image review needs to confirm that the images belong to the correct patient. While this may seem a trivial check, the consequences of using the wrong patient image for treatment planning can be significant. The patient name, ID, and date of acquisition on the images must be verified to ensure that the correct image data set is used for treatment planning. Once that is done, the following aspects of image review can proceed.

**Applicator Insertion**

The physicist should review the placement of applicators and catheters relative to the patient’s anatomy to ensure that their locations are adequate for the desired treatment. The applicator insertion should allow adequate dose coverage of the treatment target, and minimize critical organ doses.

For cervical cancer treatments, cervical markers are inserted into the cervix for identification on planar x-ray films. The optimal insertion of tandem and ovoid applicators requires that the ovoid surfaces to be at close proximity to these markers. As Katz and Eifel (2000) reported, a typical distance between the surfaces of the ovoids to the markers at M. D. Anderson Cancer Center is approximately 7 mm. Figure 1 shows a diagram of applicator geometry. Additional elements of a “good” tandem and ovoids implant include the symmetric placement of ovoids relative to the tandem both on the antero-posterior (AP) and on the lateral films, adequate distance of tandem to the sacrum and the pubis on the lateral film, and adequate packing to push the bladder and rectum away from the applicators. An inverted tandem insertion, indicated by the tandem curving toward the sacrum, may indicate perforation of the uterus (Jhingran and Eifel 2000). While patient-to-patient variations will occur, significant deviations from such typical “good geometry” should be brought to the attention of the treating physician. Such deviations may be due to the inadequate insertion of the applicators, or more likely due to the “slipping” of the applicator system caudally following insertion, and may indicate a need to re-insert and repack the applicators before patient films are acquired again for proper treatment planning.

The dosimetry of interstitial implants similarly is dependent on the adequate insertion of treatment catheters, for both coverage of target volume and minimization of critical organ doses. Clips and markers are often placed in the tumor resection margin during the surgical removal of the tumor. They should
be used to help determine the adequacy of catheter insertion. Catheter separations or the distance between peripheral catheters and the target periphery should be evaluated, as they directly impact the quality of the implant in terms of both target coverage and dose inhomogeneity. Inadequate catheter insertion should be brought to the attention of the treating physician at the earliest possible time, so that remedial actions, such as insertion of additional catheters, may be taken. Catheters near critical organs, such as the rectum in gynecological interstitial implants, may need to be left unused to avoid excessive dose to this critical organ. Alternatively, “spacers” may need to be used in these catheters to allow adequate distances between the sources and the critical organs.

The physicists performing treatment plan review should be familiar with all the applicator systems used in their institutions, especially in their physical dimensions and limitations. This is of particular relevance in HDR intraluminal treatments, such as endobronchial, esophageal, and bile duct treatments. As the HDR units typically have a limited range of distal-most and proximal-most treatable distances, the physicist should review the treatment planning films to ensure that the treatment target, as identified by the surgical markers, falls within this range, as can be identified by the x-ray markers inserted into the treatment catheters. Table 2 shows the maximum and minimum indexer lengths available in the Nucletron V2 HDR unit, together with the treatable target lengths and step sizes. Such mechanical limits are dependent on the HDR unit’s design and should be reviewed for each implant during patient imaging review.

Quality of Images and Accuracy of Imaging Parameters

Patient images, either volumetric or planar, need to be reviewed for their adequacy in allowing accurate applicator and catheter localization and dose calculations. For each type of brachytherapy implant, an imaging protocol should be developed and adhered to, with the parameters of these protocols chosen to minimize imaging artifacts, and to allow accurate applicator, target, and critical organ localization. Breathing artifacts in computed tomography (CT) scans or orthogonal radiographs will significantly

increase the uncertainties in applicator and catheter localization accuracy, as well as in the delineation of treatment target and critical organs. Figure 2 shows an orthogonal pair of radiographs for the HDR treatment of bile duct, where the patient breathing motion artifact caused up to 1 cm differences in the y-coordinates of the x-ray markers. The physicist needs to evaluate the dosimetric consequences of such imaging artifacts, and communicate with the treating physician to arrive at the optimal actions to be taken in the patient's treatment.

When volumetric imaging is used for brachytherapy treatment planning, the field of view (FOV), slice thickness, table pitch, and gantry angle of the scans need to be reviewed to ensure that they are per the scanning protocol established for the particular brachytherapy treatment. Deviations from the established scanning parameters may reduce the accuracy of applicator, target, and critical organ localization, and could result in significantly increased dose calculation uncertainties.

When orthogonal or other types of planar radiographs are used, the isocenter of the radiographs should be placed near the center of the target volume. The magnification factors of the radiographs and gantry angles need to be confirmed. The coordinate system used on the simulator, such as a Varian Ximatron unit, may be different from the International Electrotechnical Commission (IEC) coordinate system used in some treatment planning systems such as the Nucletron Plato TPS. The conversion of gantry angles between the two coordinate systems must be done correctly to avoid significant source localization errors. The filming technique used should allow clear and unambiguous recognition of applicators, surgical clips, and radiographic markers on the film.

**Target and Critical Organ Segmentation**

Image-based brachytherapy treatment planning has become common for some treatment sites, such as LDR and HDR transrectal ultrasound (TRUS) guided prostate brachytherapy, accelerated partial breast brachytherapy using either interstitial or MammoSite technique and gynecological intracavitary brachytherapy using CT/magnetic resonance (MR)-compatible applicators. The segmentation of treatment target volumes and critical organs for each patient may be performed by a radiation oncologist or a dosimetrist. The physicist reviewing the treatment plan should be familiar with the anatomy of the treated site, as well as the institutional and/or national treatment guidelines related to this part of treatment planning. The contours of segmented target and critical organs should be reviewed for both anatomical accuracy when applicable, such as the prostate, seminal vesicles, bladder, rectum for prostate implant, or the seroma and MammoSite balloon for breast implant. The expanded planning target volume (PTV) should be

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**Table 2. Nucletron V2 HDR Unit Characteristics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal Values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Treatable Distance (from indexer faceplate)</td>
<td>1500 mm</td>
<td>4 mm additional catheter length for check cable test</td>
</tr>
<tr>
<td>Minimum Treatable Distance (from indexer faceplate)</td>
<td>725 mm</td>
<td></td>
</tr>
<tr>
<td>Maximum number of dwell positions</td>
<td>48</td>
<td># of dwell positions multiplied by step size must be between min. and max. treatable distance</td>
</tr>
<tr>
<td>Step sizes</td>
<td>2.5 mm, 5 mm, 10 mm</td>
<td></td>
</tr>
<tr>
<td>Gynecological transfer tube</td>
<td>1200 mm</td>
<td></td>
</tr>
<tr>
<td>Flexible catheter transfer tube</td>
<td>1000 mm</td>
<td></td>
</tr>
<tr>
<td>Stainless steel needle transfer tube</td>
<td>1200 mm</td>
<td></td>
</tr>
</tbody>
</table>
reviewed for appropriate application of expansion margins and for overlaps with critical organs such as skin of the breast.

Review of Input Parameters to Treatment Plans

Once satisfied that the images used to construct treatment plans are of adequate quality for the purpose of treatment planning, and that the applicators and catheters are inserted to allow the desired dose distribution, the physicist can concentrate on the correctness and accuracy of applicator and catheter localization and input into the TPS.

Applicator/Catheter Geometry Parameters

The dimensions of brachytherapy applicators, catheter indexer lengths, and their numbering directly have an impact on the correctness and the accuracy of the treatment plan. Ovoid and vaginal cylinder diameters need to be verified by comparison with documented values or direct measurement from the patient images. Ovoids larger than 2 cm in diameters are often constructed by sliding a plastic cap on 2-cm diameter ovoids, and are therefore often indistinguishable from the 2 cm ovoids. The diameters of such ovoids, as well as CT/MR-compatible vaginal cylinders, therefore must be documented in the operating room immediately following their insertion. The physicist reviewing the treatment plan should review such documentation and compare the values used in the treatment plan to ensure that they are correctly recorded and used in the treatment plan. Diameters of vaginal cylinders with metal identification rings can be measured off the radiographs, and are thus readily verifiable.

Indexer lengths of HDR catheters must be reviewed carefully, with full understanding of the type of catheters used, for example, stainless steel needles or plastic flexible catheters. Depending on the transfer tubes used, treatment distance errors of up to 50 cm have occurred. Every attempt is warranted in avoiding such systematic errors that resulting in significant dose delivery errors and medical events.
Source/Applicator/Catheter Localization Accuracy

The input of sources and applicators/catheters are typically performed in treatment planning using coded x-ray markers or CT-compatible markers. The physicist reviewing a treatment plan needs to be familiar with the coding scheme of the x-ray markers, or the physical characteristics of CT-compatible markers, so that the distance information encoded in these markers can be correctly entered into the TPS.

When interstitial or intraluminal brachytherapy treatments using multiple catheters are planned, the individual catheters should be numbered, such that the source loading and/or dwell position and time calculations individualized for each catheter can be correctly reproduced in every treatment fraction. The physical numbering of the catheters needs to be compared with the data entered into the treatment plan. If coded x-ray markers are used instead of numbering of treatment catheters, the x-ray markers must remain in the treatment catheters until source loading time. The physicist should be familiar with their appearances on the radiographs or CT images.

Treatment planning systems often report source localization errors by comparing the reconstructed source length values with their expected values. These reports should be carefully reviewed to ensure that no significant errors have occurred during source localization.

The use of spacer and the value of step sizes in the treatment plan require special attention. Their locations and values need to be compared with those indicated on the patient images, and double-checked prior to treatment delivery. Errors in their use in treatment planning can result in geographically displaced dose distributions, or potentially treatment of wrong site.

Point of Interest/Critical Organ Localization Accuracy

Points of interest are often used in brachytherapy treatment plans to represent prescription point or critical organ doses. They are commonly measured on orthogonal films or from volumetric patient images, and entered manually into the TPS for calculation of doses to these points.

The localization of points of interest is of particular importance in gynecological tandem and ovoids treatment planning, as they may directly affect the overall delivery of the treatment. The classic Manchester system definition of point A measures level of point A superiorly from vaginal fornices (typically assumed to be the superior ovoid surfaces). Errors in localization of point A often result in greater than 10% error in delivered dose.

While point B, rectum and bladder points are typically not used for brachytherapy treatment prescription, their dose values are sometimes used to optimize treatment plans such as changing the source loading pattern and dwell times to reduce rectum and bladder doses, or to assist in subsequent patient management, such as the need to include parametrium boost external beam radiation treatment.

In the treatment planning for MammoSite breast treatment, the balloon diameter and its center may be measured off radiograph films. These measurements need to be reviewed for accuracy, as they are directly used for dose prescription and delivery.

For intraluminal implants or planar or volumetric interstitial implants, the doses are often prescribed to points at a given distance to the catheter(s). The placement of these points again directly has an impact on the total dose delivered to the patient. Such points may be automatically generated, such as in the case of the Nucletron Plato TPS, or manually entered for LDR treatments. The physicist reviewing a treatment plan should fully understand the mechanism through which these points are determined and localized relative to the treatment catheters and patient anatomy, and determine its appropriateness as applied to the plan under review as well as its adherence to institutional protocols.

Source Characteristics

TPS acceptance testing and commissioning usually includes a complete testing of the source characteristics, including benchmark data, physical and active source dimensions, as well as single and multiple
source dose distribution in a predetermined configuration. Treatment plan QA review therefore can concentrate on the particular sources used for a given patient treatment. Aspects of source characteristics review include verifying that the correct source model is used for the treatment plan, that the source decay was calculated accurately, and that the number of sources used in the treatment plan agrees with the prescription.

**Plan Optimization**

On a modern brachytherapy TPS, a number of automatic or semi-automatic plan optimization algorithms are typically available. While it is not the intention of this chapter to discuss these algorithms, a physicist reviewing a treatment plan, in which one of these algorithms is used, needs to have a detailed understanding of these algorithms. The selection of a particular algorithm should be specific to the goals of the treatment, in addition to keeping with institutional consistency.

Automatic optimization algorithms most often are used for the preplanning of permanent prostate implants and various HDR treatment implants. For permanent prostate implants, the optimization algorithm may be a simple geometry model that places seeds at locations in or near the prostate, based on a set of geometry rules, such as distance between needles and seeds, columns to avoid, etc. Alternatively, the optimization algorithm may attempt to distribute the seeds based on dosimetric specifications in terms of target coverage and critical organ doses. The physicist should work with the treating physician in selecting an optimization algorithm for his or her institution’s treatment planning for prostate implants. Attempts should be made to use the same optimization algorithm and optimization parameters for all prostate implants. This effort in maintaining treatment planning consistency will help achieving more predictable treatment plans in the form of a relationship between prostate volume and the number and total activity of sources. Such information is critical in determining whether a plan “makes sense,” and should help maintain consistency of patient treatment.

For HDR treatments, the selection of optimization algorithms and optimization parameters can directly impact the quality of the treatment plan as well. The Geometry Optimization algorithm (Edmundson 1990) and its variants are often used for interstitial planar and volume implants, while optimization based on dose points has been successfully used for gynecological implants (Stitt et al. 1992; Thomsen et al. 1992). The placement of dose points relative to the applicators directly affects the resulting dose distribution. Physicists reviewing such treatment plans should pay special attention to how the dose points were placed.

When dose volume histogram (DVH)-based optimization algorithms are used, the physicist should attempt to establish DVH optimization parameters for each treatment site, and subsequently review each treatment plan for its adherence to such protocols.

**Plan Quality Evaluation**

The evaluation of a brachytherapy treatment plan quality includes the aspects of target coverage and normal organ doses, as well as dose homogeneity of the plan. Similar to external beam radiation therapy, the evaluation of the quality of a treatment plan is specific to a treatment site, as well as the delivery technique used in the treatment.

**Point-based Plan Quality Evaluation Parameters**

Traditionally, brachytherapy plans based on two-dimensional radiographs do not have explicit quantitative representation of treatment target or critical organs beyond what can be estimated based on patient bony anatomy, surgical clips, or markers inserted into the patient, or reconstructed from Foley balloons and vaginal packing for gynecological treatments. When necessary, doses to these points can be calculated
as surrogates to target coverage and critical organ doses. Significant over- or underdosage to those landmarks needs to be discussed with the treating physician.

For interstitial implants, the International Commission on Radiation Units and Measurement (ICRU) (ICRU 1997) defines several parameters that are useful in the evaluation of the quality of a treatment plan. The report defines the central plane of an interstitial implant to be a plane through the major (long) direction of the implant. In practice, this often is taken to be the direction of the implant needles or catheters. For a complex implant, in which a single central plane cannot be defined with respect to all implanted catheters, subvolumes may be defined, such that a central plane may be defined for each subvolume. The mean central dose (MCD) is an extension of the basal dose of the Paris implant system, defined as the average of local minimum doses between the sources in the central plane(s) of an implant. For implants with parallel needles, the MCD can be determined geometrically as the midpoint between a group of neighboring needles. Figure 3 shows the definition of central planes and the corresponding MCD calculation for a complex interstitial implant. The Dose Homogeneity Index (DHI), defined as the ratio of the prescription dose to the MCD, has found frequent use in determining the whether a treatment plan is acceptable in terms of dose homogeneity.

Volume-based Plan Quality Evaluation Parameters

When the three-dimensional volumetric dose distribution is calculated for a brachytherapy treatment plan, additional parameters may be defined for the plan quality evaluation. Dose distribution in the treated volume, which may be calculated with only the knowledge of source locations, has proven to be useful for dose homogeneity evaluations. When a set of volumetric images is available for a given patient, dose distribution to anatomically defined treatment target, as well as organs at risk (OARs), may be critically evaluated in the quality evaluation of a brachytherapy treatment plan.

Given a dose distribution from implanted sources, the ICRU (1997) defines the high dose (HD) and low dose (LD) volumes, and the prescribed dose (PD) that help to evaluate the dose homogeneity and

Figure 3. A complex implant with two central planes defined. The Mean Central Dose (MCD) is the average of the doses at points A–G. (Reprinted from ICRU Report 58: Dose and Volume Specifications for Reporting Interstitial Therapy. Bethesda, MD: ICRU, © 1997 with permission from ICRU, Bethesda, MD.)
coverage of an implant. Details on the definitions and applications of those quantities can be found in the chapter on ICRU interstitial reporting recommendations, and are not repeated here.

A useful parameter in brachytherapy plan evaluation is the *maximum contiguous dose*, defined to be the minimum dose that encloses all sources in an implant (Neblett et al. 1985). This can be estimated on a TPS by plotting consecutively decreasing isodose clouds until an isodose cloud is seen to enclose all sources. This all-source-enclosing enclosing isodose cloud should cover the intended treatment target.

Many other tools exist that help to describe quantitatively the quality of a brachytherapy plan, especially in regard to dose homogeneity. Anderson (1995) and Thomadsen (1999) described them in detail. As many of the brachytherapy treatment planning systems today are able to calculate DVHs of various types (cumulative, differential, natural), DVH values of the treated volume, i.e., the volume of tissue receiving a given dose level, are often used for evaluation of dose homogeneity of a treatment plan, while DVH values for a given segmented organ, either target or OARs, are useful for evaluation of the target coverage of the treatment as well as risk of treatment complications. A simple plotting of the volume of an organ (the sum of voxels) receiving doses in a given range produces a differential DVH is shown in Figure 4. The cumulative DVH is calculated from the differential DVH by summing all voxels receiving doses up to a given dose level, then plotting these “cumulative” volumes against the dose levels, shown in Figure 5. A disadvantage of differential or cumulative DVH plots for brachytherapy is that, due to the high dependence of brachytherapy dose distribution on the distance between the sources and the points of interest, all DVH plots will appear similar, as demonstrated in Figure 6, which shows the cumulative DVH plot for a single HDR dwell position treatment (MammoSite), compared to the cumulative DVH of an optimized HDR interstitial breast brachytherapy treatment of Figure 5. Anderson (1986) developed a form of DVH, the *natural DVH*, which mathematically removes the inverse-square-dependence of dose.

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![Figure 4. Differential DVH plot of the treated volume of a breast brachytherapy treatment.](image)
Figure 5. Cumulative DVH plot of the treated volume of an optimized breast brachytherapy treatment.

Figure 6. Cumulative DVH of the treated volume of a MammoSite® treatment.
distribution in a brachytherapy implant, resulting in a DVH plot as shown in Figure 7. Note that a peak appears near the prescription dose of 340 cGy. In comparison, for a MammoSite breast brachytherapy treatment using a single dwell position (effectively a point source), the natural DVH appears like a flat line, as seen in Figure 8. Various parameters can be calculated from a natural DVH plot, as seen in Figure 7, that may help comparative evaluation of a treatment plan. While it is difficult to generalize the acceptable values of these parameters, in general, sharper peaks and rapid fall-off in the high-dose side of a natural DVH indicate more homogeneous dose distribution.

Saw and Suntharalingam (1991) described the dose non-uniformity ratio (DNR), defined as the ratio of a high-dose volume and the total volume of tissue receiving the prescription dose. As the magnitude of high-dose volume may be related to complications such as soft tissue necrosis, the value of DNR needs to be minimized.

When volumetric imaging is used, such as in prostate or breast brachytherapy, the target coverage and critical organ doses of the treatment plan should be evaluated based on existing institutional protocols or national guidelines. The Coverage Index (CI), defined as the ratio of PTV/CTV (clinical target volume) receiving the prescribed dose to the volume of the PTV/CTV, is typically used to describe target coverage. Significant over- or underdosage to the target or the critical organs may require modification to the plan. The physicist performing plan review should have intimate knowledge of those protocols and guidelines, and be ready to recommend revision of a treatment plan or suggest remedial action.

The use of DVH plots for brachytherapy plan evaluation can be largely empirical. Similar to external beam DVH plots, acceptable DVH values depend on the specific disease being treated, as well as the treatment technique adopted. For permanent prostate implants, the AAPM Task Group 64 (TG 64) report (Yu et al. 1999) recommended a set of DVH values. Stock et al. (2002) reported that keeping the dose that covers 90% of the PTV, D90, between 140 Gy to 180 Gy appears to be optimal, with D90 < 140 Gy.
associated with increased biochemical failure, and D90 > 180 Gy with a small increase in long-term urinary symptoms. For interstitial breast HDR treatments, Arthur et al. (2003b) recommended a set of parameters extracted from the DVH of the treated volume for evaluation of HDR accelerated breast brachytherapy treatments, as shown in Table 3.

### Independent Plan Calculation Check

An immediate question that arises after all the detailed and tedious review of the plan for a given brachytherapy treatment is why perform an independent plan check calculation? The answer to this question determines the complexity of the check calculation process and procedure. The author submits the following goals for an independent brachytherapy plan calculation check:

1. Prevention of catastrophic data input errors. Such errors may be due to misidentification of dose prescription points, incorrect data transfer, or misinterpretation of treatment prescription.

### Table 3. Accelerated Partial Breast Brachytherapy Plan Evaluation Criteria

<table>
<thead>
<tr>
<th>Volume of Treated Tissue Receiving 150% of Prescription Dose (V₁₅₀)</th>
<th>Volume of Treated Tissue Receiving 200% of Prescription Dose (V₂₀₀)</th>
<th>Dose Volume Ratio ( \left(1 - \frac{V_{150}}{V_{100}} \right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 cc</td>
<td>20 cc</td>
<td>0.75</td>
</tr>
</tbody>
</table>
2. Prevention of unexpected software errors. Even though a TPS has been subject to rigorous testing during its commissioning and acceptance testing process, it is conceivable that certain parts of the software were never tested, or the use of a specific function was never anticipated. The complexity of a modern brachytherapy TPS is such that it is impossible to test all possible functions and the sequences in which these functions are utilized to arrive at a treatment plan. As treatment planning systems are often designed with a certain operation sequence in mind, any deviation from the intended sequence may result in unexpected results.

3. Regulatory compliance. The NRC requires that all brachytherapy calculations, either manually performed or computer-generated, must be checked. While the NRC does not specify how such checks should be performed, a quantitative calculation check would appear to satisfy this requirement.

An independent calculation check, therefore, should be designed to quickly detect significant/catastrophic errors, while not significantly slowing down the treatment planning and delivery process. This is especially important in HDR brachytherapy treatments, where everything must happen in a compressed time frame.

Tools for Independent Calculation Checks

Many tools have been available, proposed, or can be modified for use for independent brachytherapy plan checks. Given the strengths or dwell times or the sources and their spatial distributions, an independent plan calculation check scheme calculates dose delivered to a given point. Considering that such algorithms have been available before the arrival of computerized treatment planning, it is no surprise that many traditional dose calculation formalisms or implant systems have found youth in the independent calculation check of brachytherapy plans. In addition to performing a gross dosimetry accuracy check, they may help provide an insight into the relationship of source strengths and resulting doses and their points of specification, compared to computerized number manipulations.

An independent plan calculation check can be done, in the more complex form, using a second brachytherapy TPS or software systems specifically developed for this purpose. Saw et al. (1998) described the use of an LDR brachytherapy TPS for the independent calculation check of HDR brachytherapy treatment plans. The source positions are transferred into the LDR TPS via digitization, with appropriate scaling of LDR source strengths to reflect the varying dwell times of HDR source at the active dwell positions. The authors stated that all calculations between the HDR system and the LDR system agreed to within 10%, with 80% of them agreeing to within 5%. Such a scheme, by its completeness, helps to identify human errors in data input as well as potential algorithmic errors in the HDR system in the aspect of dose prescription point placement, coordinate system translation and rotation, and dwell time weight optimization. The authors stated that each independent calculation check took less than 20 minutes. Cohen et al. (Cohen, Amols, and Zaider 2000) and Lachaine et al. (Lachaine, Gorman, and Palisca 2003) developed their own in-house programs to perform independent dose calculations for HDR treatments, either based on the source position input into the HDR TPS (Cohen et al.) or on the HDR treatment unit control file exported from the HDR TPS (Lachaine et al.). Cohen et al. observed a typical discrepancy of up to 3%, while Lachaine et al. saw maximum differences of 2%, compared with the HDR TPS. It should however be noted that simply transferring the already-localized source and point of interest coordinates into a second TPS and performing a second dose calculation will only verify the dose calculation algorithm accuracy, but may not detect the arguably more serious and frequent errors in source localization.

At the other end of the spectrum, classical dose calculation algorithms, such as away-and-along tables for cesium tube sources, Sievert integral (Williamson 2003) for unfiltered line sources, Paterson-Parker system (Williamson 2003) for planar and volume implants (with appropriate accounting for modern source...
strength units and correction factors, such as shown in Table 4), and prostate implant nomograms (Anderson 1976; Anderson, Moni, and Harrison 1993; Wang and Potters 2001), serve to provide quick and often as accurate estimates of the relation between total source strength and prescription dose rates.

Other methods (Mayo and Ulin 2001; Rogus, Smith, and Kubo 1998; Ezzell 1994, 2000a,b; Miller, Davis, and Horton 1996; Das et al. 2004; Cohen et al. 2002) have been developed that facilitate the quick manual calculation for specific brachytherapy treatment sites. They are typically easy to use and achieve adequate accuracy that, depending on the application, may substitute for computerized treatment planning.

Independent Calculation Check of Gynecological Intracavitary Implants

Gynecological intracavitary implants are often performed using tandem and ovoid applicators or cylinder applicators, either using cesium tubes for LDR applicators or HDR remote afterloaders. At Mallinckrodt Institute of Radiology, the loading patterns of tandem ovoids follow strict rules depending on the length of the tandem and diameter of the ovoids. Computer-generated dose values for points A, B, and P (at 6 cm away from patient midline and level of point A) can be compared to manual calculations based on the calculated, standard values in Table 5. The average of the dose values at left and right points A, B, and P, generated by the TPS, typically are within 10% of the predicted values. While the table was calculated for LDR implants, HDR treatments at Mallinckrodt Institute of Radiology have maintained the same loading pattern by weighting the dwell times accordingly. The table therefore is useful for both LDR and HDR tandem and ovoid treatments.

Mayo and Ulin (2001) described a method for checking the treatment time calculation for HDR vaginal cylinder treatments. For dose prescription points located at 5 mm away from cylinder surface in the vaginal apex region, tapering off to cylinder surface at points along the tranverse vaginal apex, the authors proposed the determination of a scaling factor $K$, that relates the prescribed dose $D$, the source strength $S$, and the total treatment time $TT$, in the form of

$$TT = K \times D/S.$$  \hspace{1cm} (1)

Given that the dose prescription points are at varying distances from the vaginal cylinder surface, the authors arrived at an equation that described $K$ as a function of vaginal cylinder diameter, the length of the cylinder with prescription point at 5 mm away from cylinder surface, as well as the length of the cylinder with prescription points on cylinder surface. The authors observed a maximum discrepancy of 5% of their independent calculation from the HDR TPS calculations.

Independent Calculation Check of Intraluminal Treatments

Intraluminal brachytherapy treatments, such as endobronchial, esophageal, and bile duct treatments, typically use no more than two treatment catheters with long active lengths. When a single catheter of relative little curvature is used for the treatment, such as is often the case for esophageal treatments, the Sievert unfiltered line source integral may be used. Let $L$ be the active length, $S$ the total source strength, $\Lambda$ the single-source dose rate constant, $x$ the away distance of the dose calculation point away from the bisector of the line source, and $T$ the total treatment time, then the dose $D$ at this point can be approximated by

$$D = 2 \times T \times \frac{S}{L} \times \frac{\Lambda}{L \times x} \tan^{-1}\left(\frac{L}{2 \times x}\right).$$  \hspace{1cm} (2)
Table 4. Paterson-Parker System Table for Plane and Volume Implants

<table>
<thead>
<tr>
<th>Volume (cm³)</th>
<th>mgRaeh·h⁻¹ 1000 'P-P'R</th>
<th>Minimum dose/IRAKe</th>
<th>Area (cm²)</th>
<th>mgRaeh·h⁻¹ 1000 'P-P'R</th>
<th>Minimum dose/IRAKe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cGy/(µGy·m²)</td>
<td></td>
<td></td>
<td>cGy/(µGy·m²)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>34</td>
<td>3.49</td>
<td>0</td>
<td>30</td>
<td>3.97</td>
</tr>
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<td>2</td>
<td>54</td>
<td>2.20</td>
<td>2</td>
<td>97</td>
<td>1.23</td>
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<tr>
<td>3</td>
<td>70</td>
<td>1.68</td>
<td>4</td>
<td>141</td>
<td>0.844</td>
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<tr>
<td>4</td>
<td>85</td>
<td>1.38</td>
<td>6</td>
<td>177</td>
<td>0.672</td>
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<tr>
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<td>1.194</td>
<td>8</td>
<td>206</td>
<td>0.578</td>
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<tr>
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<td>10</td>
<td>235</td>
<td>0.506</td>
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<tr>
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<td>207</td>
<td>0.574</td>
<td>12</td>
<td>261</td>
<td>0.456</td>
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<tr>
<td>40</td>
<td>398</td>
<td>0.298</td>
<td>20</td>
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<td>0.323</td>
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<tr>
<td>50</td>
<td>462</td>
<td>0.257</td>
<td>24</td>
<td>417</td>
<td>0.285</td>
</tr>
<tr>
<td>60</td>
<td>522</td>
<td>0.228</td>
<td>28</td>
<td>466</td>
<td>0.255</td>
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<tr>
<td>70</td>
<td>579</td>
<td>0.206</td>
<td>32</td>
<td>513</td>
<td>0.232</td>
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<tr>
<td>80</td>
<td>633</td>
<td>0.188</td>
<td>36</td>
<td>558</td>
<td>0.213</td>
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<tr>
<td>90</td>
<td>684</td>
<td>0.174</td>
<td>40</td>
<td>603</td>
<td>0.197</td>
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<tr>
<td>100</td>
<td>734</td>
<td>0.162</td>
<td>44</td>
<td>644</td>
<td>0.185</td>
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<tr>
<td>110</td>
<td>782</td>
<td>0.152</td>
<td>48</td>
<td>685</td>
<td>0.174</td>
</tr>
<tr>
<td>120</td>
<td>829</td>
<td>0.143</td>
<td>52</td>
<td>725</td>
<td>0.164</td>
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<tr>
<td>140</td>
<td>919</td>
<td>0.129</td>
<td>56</td>
<td>762</td>
<td>0.156</td>
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<tr>
<td>160</td>
<td>1005</td>
<td>0.118</td>
<td>60</td>
<td>800</td>
<td>0.149</td>
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<tr>
<td>180</td>
<td>1087</td>
<td>0.110</td>
<td>64</td>
<td>837</td>
<td>0.142</td>
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<tr>
<td>200</td>
<td>1166</td>
<td>0.102</td>
<td>68</td>
<td>873</td>
<td>0.136</td>
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<tr>
<td>220</td>
<td>1242</td>
<td>0.0958</td>
<td>72</td>
<td>908</td>
<td>0.131</td>
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<td>945</td>
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<tr>
<td>260</td>
<td>1389</td>
<td>0.0857</td>
<td>80</td>
<td>981</td>
<td>0.121</td>
</tr>
<tr>
<td>280</td>
<td>1459</td>
<td>0.0815</td>
<td>84</td>
<td>1016</td>
<td>0.117</td>
</tr>
<tr>
<td>300</td>
<td>1528</td>
<td>0.0779</td>
<td>88</td>
<td>1052</td>
<td>0.113</td>
</tr>
<tr>
<td>320</td>
<td>1595</td>
<td>0.0746</td>
<td>92</td>
<td>1087</td>
<td>0.109</td>
</tr>
<tr>
<td>340</td>
<td>1661</td>
<td>0.0716</td>
<td>96</td>
<td>1122</td>
<td>0.106</td>
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<tr>
<td>360</td>
<td>1725</td>
<td>0.0690</td>
<td>100</td>
<td>1155</td>
<td>0.103</td>
</tr>
<tr>
<td>380</td>
<td>1788</td>
<td>0.0665</td>
<td>120</td>
<td>1307</td>
<td>0.0910</td>
</tr>
<tr>
<td>400</td>
<td>1851</td>
<td>0.0643</td>
<td>140</td>
<td>1463</td>
<td>0.0813</td>
</tr>
</tbody>
</table>

1000 'P-P'R, 1000 Manchester system roentgens; IRAK, integrated reference air-kerma.


† Modified from original values for 192Ir assuming 8.6 Gy minimum peripheral dose per 1000 'P-P'R and 7.227 µGy·m²/mgRaeh·h.

Modification of the Sievert integral for HDR treatments is necessary to account for significant variations of source dwell times. In a typical HDR optimized single catheter treatment plan, the dwell times at the ends of the catheters are often significantly higher than those in the middle section of the catheter, while those in the middle section remain mostly constant. The Sievert integral, in the form above, can then be combined with point source dose calculations for the dwell positions at the ends of the catheters, to arrive at a dose estimate often within 5% of the TPS calculations.

Rogus et al. (Rogus, Smith, and Kubo 1998) investigated the relationship of catheter length and treatment distance for HDR single catheter treatments. Assuming straight-line or moderately curved catheters, the authors proposed a fitting equation for the total treatment time $t$ as shown below:

$$t(d, L)_{\text{ref}} = \left( -1.35 + 7.74 d + 0.322 d^2 \right) + \frac{L - 50}{50} \left( -0.591 + 6.92 d + 0.0230 d^2 \right),$$

for the reference condition of a prescription of 500 cGy and a source strength of 10 Ci, where $d$ is the distance of prescription point away from the catheter, and $L$ is the active length of the catheter. This equation is simply scaled to apply to other prescription doses and source strengths.

Ezzell (2000a) studied the influence of catheter curvature on dose calculation accuracy based on straight-line assumption such as outlined above, and concluded that the ratio of the distance between end dwell positions (the cord) and the active length of a single, curved HDR treatment catheter can be used as a measure of the catheter curvature. Figure 9 shows the cord-to-active-length ratio required to maintain dose homogeneity within 10% (Ezzell 2000a).

Table 5. Table for Tandem and Ovoid Plan Manual Calculation Check Used at Mallinckrodt Institute of Radiology. HDR Treatment Dwell Times Are Scaled to Achieve Identical Loading Patterns.

<table>
<thead>
<tr>
<th>Applicator Component</th>
<th>Loading (mgRaeq)</th>
<th>Dose Rate (cGy·h$^{-1}$) per mgRaeq’</th>
<th>Point A</th>
<th>Point B</th>
<th>Point P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small tandem</td>
<td>20</td>
<td>1.545</td>
<td>0.295</td>
<td>0.205</td>
<td></td>
</tr>
<tr>
<td>Medium tandem</td>
<td>10–20</td>
<td>1.543</td>
<td>0.297</td>
<td>0.207</td>
<td></td>
</tr>
<tr>
<td>Standard tandem</td>
<td>10–10–20</td>
<td>1.070</td>
<td>0.260</td>
<td>0.185</td>
<td></td>
</tr>
<tr>
<td>Endometrial tandem</td>
<td>10–20–10</td>
<td>1.308</td>
<td>0.278</td>
<td>0.195</td>
<td></td>
</tr>
<tr>
<td>2.0 cm colpostats*</td>
<td>20–20</td>
<td>0.553</td>
<td>0.250</td>
<td>0.183</td>
<td></td>
</tr>
<tr>
<td>2.5 cm colpostats*</td>
<td>25–25</td>
<td>0.474</td>
<td>0.244</td>
<td>0.182</td>
<td></td>
</tr>
<tr>
<td>3.0 cm colpostats*</td>
<td>30–30</td>
<td>0.418</td>
<td>0.228</td>
<td>0.173</td>
<td></td>
</tr>
<tr>
<td>Mini-ovoids (1.6 cm colpostats)</td>
<td>10–10</td>
<td>0.660</td>
<td>0.255</td>
<td>0.190</td>
<td></td>
</tr>
</tbody>
</table>

Multiply above numbers by total mgRaEq in each component.

*3M $^{137}$Cs tubes, 1.4 cm active length.
No correction for decay.

*Includes 6% applicator attenuation correction.

For treatments using two catheters, Miller et al. (Miller, Davis, and Horton 1996) and Ezzell (2000b) described methods to verify their treatment times. Miller et al. eliminated 50% of the active dwell positions located in areas where the two catheters overlap, such that the two catheters can be considered independently as if no overlap occurs. Ezzell’s formalism actually calculates the expected dwell time for each dwell position, based on the distance of a dwell position on a given catheter to the second catheter.
Independent Calculation Check of Planar Interstitial Implants

In general, the Paterson-Parker system applies well to the independent calculation check of planar implants. The width and the length of the implant can be estimated from orthogonal radiographs of the implant, or measured from a TPS display, with the orientation of the implant rotated to facilitate the measurement. The area of the implant thus measured can then be used for table lookup on a standard Paterson-Parker planar implant table, such as presented by Williamson (2003). The resulting mgRaeq·hrs for the implant should then be corrected for the elongation factor of the implant, and compared to the mgRaeq·hrs calculated by the brachytherapy TPS for the implant, following appropriate unit conversion. It is important to keep in mind that the original Paterson-Parker system’s prescription dose for planar and volume implants is the so-called “modal-dose,” or the dose at 10% higher the minimum dose in the surface that contains the dose prescription point. If the intention is to cover the implant volume by at least the prescription dose, the mgRaeq-hrs looked up from such a table would need to be increased by 10% to be comparable with TPS calculations.

Ezzell (1994) reviewed 66 rectangular HDR planar implants, and described a method to estimate the total treatment time required to deliver a prescription dose from the planar implant. Let $I$ be the Dose area index, defined as

$$I = \frac{\text{Dose} \times \text{area}}{\text{Source strength} \times \text{Total time}},$$

$$I = \frac{Dose \times area}{Source \ strength \times Total \ time}$$


A sample Microsoft Excel spreadsheet is available that can be used for performing these calculations, available at ftp://ftp.aip.org/epaps/medical_phys/E-MPHYA6-27-008005/example_worksheets.pdf.
then

\[ I = A(T) + B(T) \times E + C(T) \times E^2, \quad (5) \]

where \( T \) is the thickness of treatment, \( E \) is the length of the equivalent square of implant. For source strength specified in cGy cm\(^2\) s\(^{-1}\), Ezzell gave the calculations of the fitting coefficients \( A, B, \) and \( C \) as follows:

\[
A = 3.245 - 1.269 \times T + 0.1014 \times T^2
\]

\[
B = 1.030 - 0.0728 \times T
\]

\[
C = -0.02083 + 0.001925 \times T.
\]

Testing of this method on real patients showed that it mostly predicts the total treatment time to within 10%.

**Independent Calculation Check of Volume Interstitial Implants**

Volume interstitial implants can typically be easily checked by use of the Paterson-Parker tables (Williamson 2003). Das et al. (2004) reported this use for accelerated partial breast brachytherapy treatments, where better than 7% agreement was observed when corrections were made for elongation factor, and the original Paterson-Parker table was corrected for modern units. The volume of tissue treated to the prescription dose is looked up on the DVH plot calculated by the HDR TPS. When a DVH is not available, the implanted volume can be estimated by measuring the width, length, and height of the volume bounded by the implanted catheters.

The Paterson-Parker system was designed for radium sources, which are minimally attenuated in tissue. For low-energy sources such as \(^{125}\)I and \(^{103}\)Pd, used for permanent prostate seed implant, Paterson-Parker system is no longer applicable. Cohen et al. (2002) reported the use of nomograms for the independent calculation check of prostate seed implants. Let \( d_{avg} \) be the average distances between pre-planned needles/seeds in the lateral, anterior-posterior and superior-inferior directions; the authors reported the following nomograms:

\[
\frac{S_k}{U} = 1.524 \left( 1.09 \frac{d_{avg} + 0.8}{cm} \right)^{2.2} \quad (7)
\]

for \(^{125}\)I seed implants with a prescription dose of 144 Gy, treated to the prostate volume with a 5 mm margin in all directions except the posterior, and

\[
\frac{S_k}{U} = 5.395 \left( 1.09 \frac{d_{avg} + 0.8}{cm} \right)^{2.56} \quad (8)
\]

for \(^{103}\)Pd seed implants with a prescription of 140 Gy. Compared with computerized treatment plans generated using a genetic algorithm, the authors reported agreement of better than 10% in the total activity required.
Conclusions

This chapter describes briefly the goals and methods in the QA review of brachytherapy treatment plans. As modern brachytherapy treatment plans become more complex, and as the use of brachytherapy becomes more widespread, physicists are challenged constantly to come up with efficient and accurate methods to quickly evaluate the quality of a brachytherapy treatment plan. The physicist reviewing a treatment plan needs to remain vigilant in performing this important task.

References


