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Modern Imaging in Brachytherapy
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1 Introduction

The imaging revolution with Ultrasound, Computed Tomography, and Magnetic Resonance Imaging entered the world of treatment planning in external beam radiation therapy in the 80ies and 90ies, step by step (9). With the support of modern computer technology, this has led to sophisticated, widespread, 3D sectional image based treatment planning, that nowadays increasingly forms an essential integral part of daily practice treatment planning in a radiation oncology department with regard to external beam therapy. Included in this process are 3D assessment of anatomy, PTV and critical organs, 3D dose calculations with dose volume histograms, and different forms of 3D display capabilities (for example beam’s eye view, digitally reconstructed radiographs). The next step is being made by more systematically including biological models based on data derived from clinical experience. Tools are at present being developed for predicting tumour control probability (TCP) and normal tissue complication probabilities (NTCP), for example in lung and prostate cancer treatment.

For various reasons, such a development where sectional imaging is integrated into 3D treatment planning, has entered the field of brachytherapy to a limited extent only. Certainly, one of the reasons is, like in surgery, that brachytherapy is a therapeutic procedure dominated by manual skill. The link between this manual approach and dosimetry has been based on clinical examination and a clinical description of the PTV as far as possible in a three dimensional way, taking length, width, and thickness of a tumour (for example tongue, skin), and translating this via a “mental algorithm” into the dosimetry system, frequently based on projection images like radiographs. Other important reasons are certainly practical difficulties in integrating a sectional image procedure like US, CT or MRI into treatment planning and performance of brachytherapy, as for example the availability of such a system for brachytherapy. In addition, images have to be obtained with the applicator* in situ. Moreover, the commercial development of 3D treatment planning systems for brachytherapy has until recently paid little attention to the integration of sectional images into 3D treatment planning, but mainly focussed on the application of projection images for the “in space reconstruction” of the applicator and relevant anatomical points (see physics chapter 2).

However, many people have claimed that sectional image based treatment planning is an essential driving force for the further development of brachytherapy (22) which applies to the classical fields of brachytherapy like gynaecology (27) and Head and Neck (11), but in particular to new fields of brachytherapy, such as prostate (13) and intravascular brachytherapy (33). It can be stated for example that the systematic integration of transrectal ultrasound (TRUS) into prostate brachytherapy treatment planning has played a major role in the evolution of this rapidly expanding field (2). Furthermore, one has to keep in mind, that the potential for brachytherapy is enlarged by the larger number of degrees of freedom in applications (for example variations in dwell time and position of a stepping source) and also with regard to new features introduced by commercially available computer assisted treatment planning systems.

Problems arise if, parallel to this increasing potential, applications and dose calculations are not performed taking into account the large experience collected so far in brachytherapy with certain principles kept carefully in mind.

* “applicator”/“application” will be used in this chapter partly as representative for any kind of device in interstitial, intracavitary, intraluminal and contact brachytherapy.
An unsatisfactory application for brachytherapy - not taking into account the basic principles of brachytherapy - can never be transformed into a satisfactory application by any form of sophisticated computer assisted treatment planning based on sophisticated 3D imaging, for example by varying the positions and the dwell times of a stepping source. If in image assisted interstitial brachytherapy - as in general - the spacing between two needles is far too large or far too small, this inevitably leads to significant areas and volumes of under- or overdosage with the respective consequences such as local recurrence or necrosis. In such a situation, an acceptable application can only be achieved by replacing the needles or tubes with appropriate spacing related to the dimensions of the PTV as delineated on the imaging system. If the geometrical design of the needles or tubes only deviates to a minor degree from the preplanning result (incl. spacing), this can often be compensated by adapting source positions and dwell times, or by adapting the irradiation time of certain active wires, which may then result in a (rather) satisfactory dose distribution within the given PTV.

Prostate brachytherapy was significantly improved by sectional image assisted brachytherapy (endorectal ultrasound), in particular because the appropriate positioning of the seeds or needles could be improved by avoiding too large distances between the sources on the one hand, and by selectively sparing the urethra and the anterior rectal wall on the other hand.

The following chapter serves as a recommendation about the (potential) role of (sectional) imaging in different procedures of brachytherapy. It also tries to give some recommendations, under which circumstances advantages can be expected from additional (sectional) imaging.

2 Principles for Image Assisted Brachytherapy

Image based brachytherapy follows the same principles which have been developed for brachytherapy based on clinical examination and is therefore to be regarded as a complementary tool (for example in gynaecology, head and neck, breast). However, in some areas (in particular in deep seated tumours) image assisted brachytherapy represents a major or the only tool for planning and performance of brachytherapy, as in prostate, brain, oesophagus, bronchus, bile duct, vessels.

Therefore, the fundamental process of “clinical examination based treatment planning and performance of brachytherapy” is the starting point to assess appropriate methodology for “image based brachytherapy”, which consists of provisional dose calculation and treatment planning, application, definitive dose calculation and treatment planning, and dose delivery.

Systematically, image based brachytherapy is therefore following a logical schedule with the different steps as outlined in table 1.

This process with its four systematic steps is in principle to be followed in image based brachytherapy.

One major issue in image assisted treatment planning in brachytherapy introducing a major difference to external beam treatment planning, is that irradiation in brachytherapy is performed through an applicator or a radioactive source brought into, or next to, the tumour, by which tumour topography and topography of organs at risk is often significantly changed. Therefore, in brachytherapy treatment planning, there is a separation between provisional image assisted treatment planning without an applicator or with a dummy applicator and definitive image assisted treatment planning with the applicator in place.
The most important issue in brachytherapy, however, is the application itself, nowadays most often performed as afterloading technique. The position of the applicator in relation to the PTV and the organs at risk is the most crucial point for appropriate dose distribution. In order to arrive at the best result possible, images are therefore not only used for treatment planning, but also for direct guidance of the application, as for example in prostate (US) and brain brachytherapy (MRI/CT) and in some other situations like bronchus (ES) or vessels (CR) for deep seated targets.

**Table 5.1: Schedule for the different steps of image assisted brachytherapy**

<table>
<thead>
<tr>
<th>IMAGE ASSISTED PROVISIONAL TREATMENT PLANNING (treatment simulation and provisional dose calculation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>conventional radiography (CR); sectional imaging: MRI, CT, US, (PET) light imaging: endoscopy (ES)</td>
</tr>
<tr>
<td>IMAGE GUIDED APPLICATION</td>
</tr>
<tr>
<td>CR, MRI, CT, US, ES (with or without on-line treatment planning)</td>
</tr>
<tr>
<td>IMAGE ASSISTED DEFINITIVE TREATMENT PLANNING</td>
</tr>
<tr>
<td>Imaging after application for definitive treatment planning (CR, US, CT, MRI)</td>
</tr>
<tr>
<td>IMAGE ASSISTED QUALITY CONTROL OF DOSE DELIVERY</td>
</tr>
<tr>
<td>Imaging for quality control during or after brachytherapy (CR, CT, MRI)</td>
</tr>
</tbody>
</table>

Finally, **image assisted quality control of dose delivery** is performed dependent on the duration of brachytherapy (LDR, PDR, (HDR)). It is essential, that this image assisted quality control be performed by the same imaging method, by which definitive treatment planning has been done. It has to be taken into account that the patient with the applicator and/or the radioactive sources has to be taken to the imaging device (for radiography, CT, US, MRI).

The impact of imaging varies significantly in the different fields of brachytherapy. With regard to imaging, prostate brachytherapy at present represents the most comprehensive approach going through all these steps systematically.

The essential step in treatment planning for brachytherapy is the **delineation of the GTV, the PTV and the organs at risk in relation to the applicator**. Imaging contributes in different degrees to this detailed delineation of the GTV and to the determination of the PTV in its three dimensions related to the applicator position and later to dose planning. In principle, the impact of imaging on this process depends mainly on the impact of imaging on the specific tumour and the specific site.

**Nowadays, the following imaging procedures are recommended** which enable best the delineation of the GTV and the determination of the PTV for the different sites (Table 5.2) (3). Endoscopy also plays a major role in various sites. The certainty of the GTV delineation varies somewhat depending on the site and the imaging method available. If the GTV is accessible by clinical examination (e.g. head and neck, skin, gynaecology, prostate), the findings must be related to each other and be weighted against each other. The same applies for findings from endoscopy and other imaging procedures, as for example in the oesophagus and the bronchus. Sometimes, these findings are complementary, as for example in the bronchus or in the oesophagus, where the lumen is best investigated by endoscopy and barium swallow and the wall and the transverse tumour extension best investigated by sectional imaging (CT, intraluminal US).
This comprehensive approach is also valid for cervix and vagina, where, in addition to the clinical examination and a vaginal impression by a mould, the depth of infiltration can be investigated accurately by sectional imaging like MRI and intraluminal US.

Different applicators are used for specific tumour sites according to specific demands and possibilities at these sites from a clinical and dosimetric point of view. In addition, for an applicator to be useful, certain requirements must be met for a specific imaging technique detailing visibility, reliability and reproducibility of the applicator with as little negative impact as possible on the imaging quality of the tumour and the organs at risk and with no negative impact on the geometrical accuracy of the image. These requirements vary with the imaging technology used and are met to different degrees by specific devices: for ultrasound by echogenic needle tips (for example for prostate); for CT by applicators not producing metallic artifacts; for MRI by non-metallic applicators and needles (for example for gynaecology). In some situations, for example for the vagina and for the anorectal region, it is advisable to introduce image compatible dummy applicators or moulds in provisional treatment planning to provide similar topographic conditions for provisional and definitive treatment planning.

Table 5.2: Overview of imaging procedures for delineation of the Gross Tumour Volume and for determination of the Clinical and Planning Target Volume for different sites of brachytherapy; Endoscopy (ES) is added, if indicated

<table>
<thead>
<tr>
<th>Tissue/Region</th>
<th>1st choice</th>
<th>2nd choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile Tongue</td>
<td>MRI</td>
<td>CT</td>
</tr>
<tr>
<td>Floor of mouth</td>
<td>MRI</td>
<td>CT</td>
</tr>
<tr>
<td>Buccal mucosa</td>
<td>MRI, CT, US</td>
<td>CT</td>
</tr>
<tr>
<td>Oropharynx</td>
<td>MRI, ES (CT)</td>
<td>CT</td>
</tr>
<tr>
<td>Nasopharynx</td>
<td>ES, MRI (CT)</td>
<td>CT</td>
</tr>
<tr>
<td>Lip</td>
<td>MRI</td>
<td>CT, US (endo)</td>
</tr>
<tr>
<td>Cervix</td>
<td>MRI, ES</td>
<td>CT, US (endo)</td>
</tr>
<tr>
<td>Endometrium</td>
<td>US (endo), MRI</td>
<td>CT</td>
</tr>
<tr>
<td>Vagina</td>
<td>Mammography, MRI</td>
<td>CT, US</td>
</tr>
<tr>
<td>Breast</td>
<td>ES, MRI, CT</td>
<td>US</td>
</tr>
<tr>
<td>Bladder</td>
<td>MRI</td>
<td>US (endo), CT</td>
</tr>
<tr>
<td>Prostate</td>
<td>MRI</td>
<td>US, CT</td>
</tr>
<tr>
<td>Penis</td>
<td>MRI, US (endo)</td>
<td>CT</td>
</tr>
<tr>
<td>Anorectal</td>
<td>ES, MRI, US (endo)</td>
<td>CT, MRI, US (endo)</td>
</tr>
<tr>
<td>Oesophagus</td>
<td>ES, Oesophagogram (Barium)</td>
<td>CT, US, MRI</td>
</tr>
<tr>
<td>Bile duct</td>
<td>Cholangiogram, ES</td>
<td>CT</td>
</tr>
<tr>
<td>Soft tissue sarcoma</td>
<td>MRI</td>
<td>MRI</td>
</tr>
<tr>
<td>Bronchus</td>
<td>ES, CT, Chest X Ray</td>
<td>CT</td>
</tr>
<tr>
<td>Skin</td>
<td>Angiography, US (IVUS)</td>
<td>MRI</td>
</tr>
<tr>
<td>Brain</td>
<td>MRI</td>
<td>CT</td>
</tr>
<tr>
<td>Eye</td>
<td>fundoscopy, US, angiography</td>
<td>MRI</td>
</tr>
<tr>
<td>Intravascular</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Specific investigation protocols are set up and adapted based on diagnostic imaging for a given tumour site in order to achieve optimal results with regard to high quality simultaneous imaging of the applicator, tumour and the surrounding tissue.
Contrast media for CR and CT have to be carefully considered as well as specific acquisition protocols/sequences and contrast media for MRI. These protocols differ for different brachytherapy sites, applications and may also vary to some extent through the different steps of the planning process.

In image assisted brachytherapy, the method of sectional image acquisition is to be decided taking into account the specific application technique. The main issue in imaging for brachytherapy is always to display the tumour in relation to the applicator as accurately and reproducibly as possible. The best fit to the topographical and dosimetric situation with the applicator in place can be achieved if sectional images are taken, in three dimensions parallel and perpendicular to the (projected) axis of the applicator and needles or tubes (25). By this technique, the image section represents the plane along or perpendicular to which irradiation will be performed. The highest accuracy can be achieved in estimating tumour dimensions related to the projected applicator geometry and dose distribution by using such image orientation.

Fig 5.1: Different MRI/CT compatible applicators
A: interstitial brachytherapy; plastic needles, plastic implant tubes, titan needles, plastic templates (Nucletron, Popowski)
B: intracavitary and intraluminal brachytherapy: CT and MRI gynaecologic applicators for cervix cancer (carbon ring applicator, intrauterine tube with vaginal cylinder), endometrial cancer (Norman Simon catheters), and for vaginal treatment (cylindrical applicator) (Nucletron) (for further intraluminal MRI/CT compatible applicators compare Fig 5.4 oesophagus)

Classical examples are the following procedures: sagittal (parallel), paracoronal (parallel) and paratransverse (90°) images (endorectal ultrasound) related to the needle axis in prostate cancer; (para)sagittal (parallel), paracoronal (parallel) and paratransverse (90°) images (MRI) related to the axis of the cervix canal and the uterine cavity in uterine cancer; sagittal (parallel), paratransverse (90°) and paracoronal (parallel) images (MRI) related to the axes of the tubes in tumours at the base of the tongue; sagittal, paracoronal, and transverse planes (CT) perpendicular to the axis of the oesophagus in oesophageal cancer; the appropriate 3D image acquisition (MRI) for planning a brain implant depends on the axis of the projected needles and the specific topography. At present, the best method for image acquisition enabling a free slice orientation is MRI. However, 3D ultrasound and multislice CT will, in future, also contribute to the potential of 3D imaging.
Reliability of the applicator system with the specific material used has to be checked carefully for the respective imaging system with regard to dimensions and topography.

Geometrical accuracy is assumed to be almost perfect in CR (projection film imaging), CT and ultrasound. Fluoroscopy only provides sufficient geometrical accuracy around the centre of the screen. Distortions from MRI – depending on field strength and image acquisition protocol – do not play a major role in image assisted brachytherapy, if some basic variables of MRI image distortion are taken into account (8). As there is usually minor distortion around the centre of the magnet, this area should consequently correspond to the centre of the region of interest on the image (PTV) and to the projected applicator.

Reproducibility of the topography - as presented on the image - comparing provisional and definitive treatment planning (including quality control) means how far the anticipated and the actual geometry will match. This mainly depends on the applicator position, its impact on the topography of the tumour and the organs at risk and also on tissue changes (for example oedema) taking place after application. In order to achieve a high degree of reproducibility, organ movement and organ filling are the major parameters which have to be carefully controlled. Furthermore, the conditions for image acquisition are to be kept as identical as possible. This can be best achieved when using CR, CT, and MRI and is somewhat more difficult when using ultrasound, due to the variable positioning of the ultrasound device.

Fig 5.2: Applicator geometry and selection of appropriate image orientation shown for an intracavitary gynaecologic brachytherapy with a ring applicator in place using MRI: the slice orientation is chosen parallel and orthogonal to the axis of the intrauterine tube and the coronal (C) and sagittal (A,B) midplane of the ring: parasagittal (C), paracoronal (A), and paratransverse (B). The cervix cancer (high signal intensity) can be clearly discriminated and the tumour topography can be precisely related to the applicator.
There are different ways of handling the image information for treatment planning (level 1-3, part 7 of this chapter). The most accurate and reliable method is to enter the **image information directly into the treatment planning system**. Film radiographs are still widely used and usually have to be digitised first. These projection images may then be linked to the sectional images taken. There are different methods available to do this matching procedure, which is at present usually based on applicator landmarks (fixed, non fixed) and/or on anatomical landmarks. The digital sectional images can usually be entered directly into the treatment planning computer (via network). Treatment planning can also be directly based on sectional images (Fig 5.3).

**Modern Imaging in Brachytherapy**

*Fig 5.3: Infrastructure for modern imaging based brachytherapy integrating all information from the different forms of imaging into provisional treatment planning, into image guided procedures and into definitive treatment planning for brachytherapy. Networking between the different imaging devices and the brachytherapy treatment planning system is a precondition for practical use.*
3 Image Assisted Provisional Treatment Planning  
(treatment simulation and provisional dose calculation)

Classical (provisional) treatment planning for brachytherapy begins with the clinical examination of the patient for delineation of the GTV and for determination of the PTV for brachytherapy. The clinical examination results in a clear and reproducible 3D documentation (drawing and/or photography) of the gross tumour and a 3D delineation of the PTV, indicating width, length and thickness and as far as possible the topography related to surrounding structures. Based on these findings, the application is planned in detail starting with a provisional plan for the technique and for dose calculation. This plan must ensure that the application is feasible, that the PTV will be treated with the prescribed dose and that normal tissue at risk within and/or without the target will not be irradiated beyond a prescribed tolerance limit.

Image assisted provisional treatment planning for brachytherapy tries to follow the same principles taking advantage of the capabilities of the respective imaging method. Imaging should be performed taking into account the technique of the planned application, in particular the direction of the applicator (see above). Imaged assisted provisional treatment planning must result in a delineation of the GTV and determination of the PTV in relation to the organs at risk in three dimensions, which is then reliably and reproducibly documented on the images, ideally together with a dummy applicator or at least together with the planned position of the applicator. The dimensions of the GTV and PTV, indicating width, thickness, and length/height in mm are given in relation to the applicator and the volume. The configuration of a tumour is, of course, more accurately represented on a MRI or CT than these measurements indicate. Thus, in imaging assisted brachytherapy - in addition - the specific spatial 3D configuration of the tumour and the critical organs provides the basis for detailed individualised planning which enables a highly 3D adapted and individualised application. This procedure is comparable to a detailed clinical examination with inspection, palpation and documentation of a clinically well accessible small tumour (e.g. skin, lip, mobile tongue) for treatment planning.

Based on the comprehensive view of all information which can be provided by clinical examination and imaging, a provisional plan, as well as the provisional dose planning of the application, is set up for the technique. As the situation varies considerably with the technique of application (interstitial, intraluminal, intracavitary, contact) and the tumour site, this must be taken into account carefully.

For the provisional planning procedure the “internal” topography of the tumour and of the nearby organs at risk is crucial, the “external” positioning of the patient is not as important as in external beam therapy. Therefore, conditions which are important for a reproducible “internal” topography (e.g. organ filling) should be kept as similar as possible.

The coverage of the PTV by the treated volume for a given application geometry can be accurately estimated in provisional image based treatment planning. However, the adequate software tools available today in the treatment planning systems are of limited value.

3.1 Interstitial brachytherapy

For interstitial brachytherapy, based on clinical and imaging information available with regard to the dimensions, configuration, and clinical accessibility of the PTV, the overall arrangement of needles and/or tubes is determined: orientation, length, separation, number, configuration (straight or curved lines, triangles, squares), equidistance and parallelism, template.
For a brachytherapy boost treatment, for example in a tongue carcinoma infiltrating the anterior faucial arch, the dimensions of the GTV measured along the axis of the tongue are 35 mm in length, 30 mm in width, and 25 mm (thickness) into the depth of the tongue. A safety margin of 5 mm may be chosen in all directions resulting in a PTV with a length of 45 mm, 35 mm width, and 30 mm thickness. Provisional dose planning based on drawing and on the rules given in the Paris System, for example, reveals that - taking the transverse central plane - three planes of straight plastic tubes perpendicular to the surface of the tongue with 4 tubes in each plane implanted as triangles with 12 mm spacing are sufficient to cover the CTV with the prescribed dose. The prescribed dose is referred to the mean central dose and is supposed to be > 80% of the MCD (high homogeneity index).

Fig 5.4: Provisional treatment planning for a brachytherapy boost in tongue cancer based on clinical examination and MRI.
A-C: MRI study (T2 weighted, Proton density weighted, fat suppression) in coronal, sagittal and axial orientation indicating the GTV in its configuration and the different dimensions which are according to MRI in width 30 mm, in length 35 mm and in thickness 25 mm (14 cm³) similar to those found by clinical examination.
D: Provisional treatment planning based on the information of the clinical examination and the MRI study: Eleven needles placed in triangle configuration with spacing of 12 mm are planned to cover the PTV (GTV plus 5 mm margins). The mean central dose is 60 cGy, the prescribed dose encompassing the CTV 50 cGy. The maximum dimensions of the treated volume are 34 mm in width, 43 mm in length, and 35 mm in thickness, the treated volume is 23 cm³ ("V100"). The dose homogeneity index is 0.83, the high dose volume (90 cGy isodose) is 3 cm³.
The high dose volume is low. Imaging reveals some clearly reproducible information, which is also included in the clinical findings: the spatial tumour configuration is such, that width, thickness and length are changing throughout the volume. Because of these findings, the width and length are adapted to the specific variations of these parameters throughout the volume, as far as possible slice by slice. This influences the dose distribution in each slice. In certain situations, critical organ structures can be delineated (e.g. mandible in floor of the mouth brachytherapy).

The dose distribution inside the PTV, in particular with regard to the volumes of high doses around the needles, must be studied in detail, which is in some contrast to the practice of external beam therapy with the flat dose profile, where most attention is paid to the encompassing isodose. In interstitial brachytherapy the rapid dose fall-off near the sources leads to high dose regions and overall to a significant inhomogeneity within the treated volume. These high dose volumes need to be studied in detail. However, between the sources the dose gradient approximates a dose plateau and local minimum doses can be defined, which serve for dose specification: the mean of these local minimum doses for the whole implant is the mean central dose. If a high homogeneity ("homogeneity index" (16)) is to be achieved within the treated implant volume, the isodose encompassing the PTV is as closely as possible related to this dose plateau. (compare 6.6 reporting in brachytherapy). This homogeneity index may vary between 75%, 80% or 90%. It is 85% in the Paris System. In order to arrive at such homogeneity, the best way is to start with the central dose points, calculate the mean central dose (MCD) and find an appropriate isodose, related to the MCD, encompassing the PTV. The need for a high homogeneity index results from a long clinical experience in non image based brachytherapy in avoiding serious adverse side effects, e.g. along the traditions of the Paris or Manchester School. This requirement seems to apply for most interstitial applications where normal radiosensitive tissue is included within the target, as in head and neck tumours, breast cancer, bladder and penis cancer, anorectal tumours, soft tissue sarcoma, skin tumours. It may not apply, for example, to prostate tumours with regard to the prostate tissue (but to urethra).

Whereas provisional image based treatment planning as demonstrated for head and neck cancer is only under development, which also applies to other areas of interstitial brachytherapy (e.g. gynaecology), this procedure has proven to play a crucial role in prostate brachytherapy (Fig 5.5).

Fig 5.5A Provisional ultrasound based treatment planning and dose calculation for a prostate brachytherapy application. The first and second step (A/B) are identical for the different techniques used in prostate brachytherapy (LDR, HDR, PDR):

Fig 5.5A: Diagram of the endorectal ultrasound prostate (volume) study using the stepper unit, for advancing the ultrasound probe systematically and reproducibly with the fixed template allowing precise definition of the 3D co-ordinates of the needles with their tips (courtesy of G. Kovacs Kiel). The transverse ultrasound prostate images are taken in orthogonal orientation related to the projected direction of the needles. The resulting 6-10 transverse ultrasound images are 5 mm thick and directly adjacent to each other. Dimensions of the prostate are indicated. The volume is calculated by automatically adding the measured plane of the prostate multiplied by each slice thickness in each transverse ultrasound slice.
3.2 Intraluminal Brachytherapy

For **intraluminal treatment** image based brachytherapy may include different procedures depending on the purpose of treatment.

In a **definitive treatment setting with curative intent**, a comprehensive approach is used, as the contribution of intraluminal brachytherapy to local control and cure is essential. Therefore, for the definition of PTV, gross tumour thickness, and length are measured exactly, based on clinical examination, endoscopy, CT/MRI and/or US. Tumour thickness means the radial distance from the luminal surface to the outer tumour border. Accurate measurements and imaging make it possible to precisely define the GTV, the PTV, and the position of the prescription point, and to estimate in how far the prescribed dose will - in ideal geometry - encompass the PTV (Fig 5.6). However, the image based provisional dose planning in these cases only allows for a rough estimate, as the application itself may change the topography considerably (vagina, oesophagus), or as the tumour relation to a small diameter applicator in a large lumen (bronchus) can only be accurately determined during the procedure itself (Fig 5.7).
In small tumours with a thickness of only a few millimetres, provisional dose planning will, in principal, reveal that the therapeutic isodose can encompass the PTV (e.g. the whole wall), if – in ideal geometry - the prescription point can be adequately chosen (e.g. at 5-7 mm from the applicator surface). If the tumour thickness related to the luminal surface is significantly thicker than 5 mm, an adequate coverage of this PTV is only possible with a large diameter applicator allowing in addition some overdosage to the mucosa/submucosa, which may be critical. In image based planning of such application, as much as possible of the overdosage volume - receiving more than 200% of the prescribed dose – should be within the applicator itself. This relation is mainly dependent on the diameter of the applicator, its topographical relation to the wall and to the PTV and the prescription point (see chapter on oesophagus). If for example a large thick tumour as shown by imaging (e.g. >10mm) is to be treated, and if intraluminal brachytherapy is regarded as an essential treatment option, it is appropriate to start with external beam therapy. In such case a significant dose of intraluminal brachytherapy applied to the PTV within a boost treatment is only possible after significant tumour shrinkage. In such combination treatments, the respective examinations have to be repeated at the time of brachytherapy in order to be able to delineate precisely the actual GTV at this point, the PTV and the lumen dimensions and to base the technique of application and the dosimetry on these findings.

**Fig 5.6: Recurrence at the stump of the left upper lobe bronchus.**

A: Endoscopic image

B: Drawing in the "bronchial tree" showing the accurate topographic relations and the dimensions related to the bronchus lumen: 18 mm in length and 7 mm in thickness. Curative treatment with brachytherapy alone.
Fig 5.7: Intraluminal brachytherapy in bronchus cancer as demonstrated on a transverse CT-image. Eccentric position of a 1.7 mm diameter bronchus applicator in the wide right main stem bronchus (diameter 9 mm); concentric position of the same applicator in the small lumen of the intermediate bronchus (2 mm), which is obstructed by tumour. If 6 Gy is prescribed at 10 mm from the source axis - as usual in intraluminal bronchus brachytherapy - the dose at the applicator/lumen surface will increase with its maximum near the dwell position up to a factor of about 13, i.e. ~75 Gy. The maximum value decreases down to ~ 20 Gy between two dwell positions. (compare Fig 6.17-20 and 26.5).

In the postoperative treatment of the vagina in endometrium cancer, no additional imaging is used for the determination of the target in the adjuvant setting, as there is a standard prescription point (e.g. at 0, 3, 5 mm from the applicator surface) and a reporting point at 5 mm from the applicator surface (into the vaginal wall). However, if a significant radiation dose is applied by brachytherapy alone, or combined with external beam as for example in definitive treatment of vaginal cancer, in vaginal metastases or in vaginal recurrence, it is advisable, to precisely assess the dimensions and the configuration of the GTV (thickness and length), and also the thickness of the vaginal wall by means of intravaginal/endorectal ultrasound with and without the impact of the expanding intraluminal applicator (Fig 5.8). There is a considerable variation in vaginal wall thickness (values from 1-7 mm). The choice of the technique of application (intraluminal/interstitial) and the determination of dosimetry is then based on the clinical findings including this additional imaging information.

In bronchus and oesophageal cancer the tumour and organ dimensions are examined by endoscopy (Fig 5.6), radiography (oesophagus: barium swallow) with regard to intraluminal dimensions, and CT (Fig 5.7), MRI, and intraluminal ultrasound (oesophagus) for tumour extension in transverse orientation (compare chapter 24 on oesophagus and 26 on bronchus). These examinations are to be repeated in combination treatment before brachytherapy.
In a **palliative treatment setting** as most often in oesophageal and bronchus cancer a straightforward procedure is chosen, as the main goal is to enable desobliteration of the lumen for a certain time period, which means to **treat by brachytherapy the desobliterating part of the tumour**. Related to imaging (ES and/or radiography), the main issue is the assessment of the length of the GTV (e.g. x mm) and the determination of the length of the CTV (e.g. x+10-20 mm each on the proximal and distal part) and the lumen diameter. In bronchus cancer, the determination of length and lumen diameter is done by bronchoscopy, documented on the “bronchial tree” and must be translated onto conventional radiography, for example by relating the macroscopic disease and its longitudinal dimension unambiguously to a certain anatomical landmark, for example the carina taking into consideration the magnification factor (see bronchus chapter (26)).

In oesophagus cancer, endoscopy and/or barium swallow allow estimation of the length of macroscopic disease (see Figure 24.3); for radiography based treatment planning the magnification factor must be taken into account. The tumour topography and its longitudinal dimensions are to be related to fixed anatomical structures (teeth in endoscopy, e.g. tracheal carina in barium swallow). Information about the diameter of the lumen is to be obtained based on endoscopy and/or barium swallow. This diameter is crucial for the application technique (diameter in oesophagus) and for dosimetry. The prescription point, which is in clinical practice often related to the applicator axis in small diameter applicators and to the applicator surface in large diameter applicators, is defined for the therapeutic dose which is related to the obliterating part of the tumour (inner part of the wall) and not to the whole (extramural) tumour extension in this palliative setting.

In **intravascular brachytherapy** angiography is routinely used for planning, providing the diameter of the vessel and the length of the lesion which has been dilated. In addition, intravascular ultrasound is used for the assessment of individual radial topography and pathology.
Fig 5.9: Coronal and sagittal MRI (A,B) in obstructive advanced oesophageal cancer (T3,N2,M0) with a 4 mm diameter applicator in place. The thickness of the macroscopic tumour was maximum 8 mm to the right and 12 mm to the left, 8 mm to the anterior and 6 mm to the posterior direction. Palliative treatment with brachytherapy for desobliteration of the inner part of the tumour was performed with 3 X 6 Gy prescribed at 10 mm from the source axis, which is at 8 mm from the lumenal surface. Dose at 5 mm from the applicator surface was 10 Gy, at the lumenal surface (lumenal part of the tumour) the radiation dose was >30 Gy for each fraction (compare Fig 6.18,19 and 24.3-10).

3.3 Intracavitary brachytherapy

Provisional dose planning is not routinely used these days in image based intracavitary brachytherapy. Image based determination of the GTV (dimensions, configuration) – in particular based on MRI – facilitates (in addition to clinical examination) the decision on the adequate application technique, adequate time of application (after shrinkage of a large tumour) and an estimate of the achievable dose distribution. For example, it can be clearly foreseen that a tumour, as seen on MRI, advancing in one lateral direction by 4 cm and measuring 5 cm in thickness will not be encompassed by an adequate radiation isodose by any kind of intracavitary treatment. Such estimate is difficult in a tumour with a 2 - 3 cm unilateral extension and a thickness of 2 - 3 cm. The position of the applicator in relation to the GTV must be taken into consideration and can hardly be foreseen precisely. Furthermore, topography usually changes considerably by insertion of the applicator. Therefore, accurate image assisted dose planning should, in principal, be based on images (MRI) with the (MRI compatible) applicator in place related to the tumour and normal tissue topography (see Fig. 14.14).

3.4 Contact brachytherapy

In contact treatment provisional dosimetry based on imaging is of limited value, with the exception of eye plaque therapy where the tumour is not directly accessible to clinical examination. Thus, in provisional dosimetry for eye plaque treatment precise information on the tumour diameter,
thickness and topography is obtained from transillumination, fundoscopy, and imaging (ultrasound). The technique of application and the most appropriate plaque or seed distribution is chosen based on this information (see for eye melanoma Fig. 30.3 and 8).

4 Image guided Application

By definition, in imaged guided application, the application is done under guidance of an image procedure.

Image guided brachytherapy follows the principles of brachytherapy based on, and guided by, “stereotactic” clinical examination (i.e. vision and palpation in clinically accessible tumour sites). In the majority of cases, the imaging procedure contributes to the clinical examination. If imaging tends to replace the visual part of the clinical examination (for example in prostate, brain, endometrium), it is to include as many features of the clinical visual capabilities as possible, which mainly means 3D imaging. One major tool for image guided applications is the integration of a 3D co-ordinate system into the imaging and application procedure.

The ultimate solution at present seems to be represented by application integration into a 3D navigation system.

The main precondition for image guided application is the availability of an imaging device for brachytherapy, its suitability for the support of the application and its adaptability to the specific needs of the application.

As such devices have been comprehensively developed for prostate brachytherapy, the different elements for ultrasound guided brachytherapy can best be studied going through this example. A dedicated stepping device has been developed, advancing an endorectal ultrasound probe reproducibly for the support of needle and seed positioning. The target (prostate) is imaged during the application in transverse slices, with the probe stepping along the longitudinal direction from base to apex of the target (prostate) in fixed step sizes (5 mm). The stepping device has a fixed starting position, which serves a reference position for the longitudinal direction. A grid representing the template with its holes is superimposed on each slice and gives precise co-ordinates for the different positions of the needles and seeds. By this procedure each needle and seed can be accurately positioned in a 3D co-ordinate system - exactly at the place determined in advance during the preplanning procedure.

In case of topographic deviation, this is taken into consideration during final dosimetry based on images taken during and/or after the application. Another possibility is on line dosimetry during the application. The ultrasound images and the 3D co-ordinate system are directly linked to the computerised treatment planning system. During the application, the actual dose distribution by placing the needles and seeds can in some systems be visualised directly and – if necessary – adjusted.

A similar procedure – however less sophisticated – is used in endorectal ultrasound guided interstitial brachytherapy of vaginal and paravaginal tumours (compare for interstitial gynaecologic brachytherapy Fig 16.7, 17.8).
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Fig 5.10: Ultrasound and fluoroscopy guided brachytherapy for prostate cancer with a dedicated stepper unit with a template, a specific device for endorectal ultrasound linked to the stepper unit with the grid of the template superimposed on the transverse ultrasound image (B&K), and a fluoroscopic device, all in the operating theatre. The white arrow indicates the needle position at the template, on the transverse ultrasound, and on the fluoroscopic screen.

The needles are prepared, loaded with iodine-125 and placed in the XYZ co-ordinates determined during the provisional ultrasound based treatment planning procedure. Adaptation of the co-ordinates may be performed during an on-line treatment planning procedure based on actual ultrasound images taken during the implantation (compare Fig 5.5, 5.13, and 5.16).

At dedicated places MRI or CT guided brachytherapy is performed for brain tumours based on principles of stereotactic localisation techniques (see Chapter 29). This also includes an adequate provisional treatment planning procedure with MRI or CT imaging using the same stereotactic frame as for the application (reproducible 3D co-ordinate system). The needles or seeds can be positioned under MRI or CT guidance in predetermined positions using the 3D stereotactic co-ordinate system. For deep seated tumours of the head, specific CT or MRI based 3D navigation systems have been developed (1, 20).

Some clinical experience has been collected using CT and MRI guided brachytherapy techniques for different tumour sites (MRI: liver, pelvis; CT: various (palliative) indications in the head and pelvis (Fig 5.11 and 5.12)). The use of templates for needle guidance (being represented on the images together with the target and the critical organs) may be efficient for image guided brachytherapy replacing a complex 3D coordinate system: the distances (template-distal end of the target), the angulation and the spacing of the needles can be exactly determined in advance and during the procedure. Similar to interventional radiology techniques, the adequate needle placement is directly supported by imaging through various different procedures (e.g. Seldinger technique like in angiography).
Fig 5.11: CT guided brachytherapy (Somatom Plus, Siemens) for residual disease of a pelvic wall recurrence in a patient with cancer of the uterus as a boost treatment after 60 Gy to the pelvic wall and significant tumour shrinkage. Three round plastic needles with an obturator are forwarded by free hand technique retroperitoneally from the anterior lateral pelvic wall. For orientation transverse CT images are first taken, by which the position and the angle for the needle placement is determined (A). The needle is forwarded under the given angle a few cm and a control CT image is taken (B,C). The procedure is further supported by imaging, as appropriate for the precise positioning of the needles (D). At the end of the procedure transverse CT images are taken for the whole volume implanted and dose calculation is based on these images, which are directly introduced into the treatment planning system (E). (Three fractions of HDR brachytherapy were given in 24 hours with 6 Gy each to a total dose of 18 Gy with a treated volume of 15 cm³. No evidence of local tumour regrowth and of side effects 18 months after treatment with progressive disease at distant sites.)

A: CT image for orientation indicating the position and the angle for introducing the needle;

B: Needle placement at a computer tomograph (complete view);

C: Two guide needles in place for orientation (right anterior pelvis, different patient, same procedure);

D: CT image with 1st and 2nd plastic needle in place;
Fig 5.12: MRI guided interstitial brachytherapy application in pelvic malignancies (recurrent or extensive gynaecologic cancer, recurrent or R2-resection in T4-rectal cancer). The procedure is performed at an open MRI unit (Magnetom Open Viva, Siemens), partly directly guided by imaging with a touch screen for on line view (A), partly directly linked to the MRI unit in the same room (B). The operating table with the patient can be directly advanced under the MRI unit, without significantly changing the patient’s position. All tools for the procedure have to be MRI compatible.

E: Dose distribution indicating different isodoses encompassing the PTV.
5  **Image Assisted Definitive Treatment Planning**  
(imaging with the applicator in place for definitive dosimetry)

Imaging for definitive treatment planning has to be performed under the same conditions present during brachytherapy treatment. The main issue is the reproducibility of topography. Specific care has to be taken that patient and applicator position as well as organ position (e.g. bladder and rectal filling, breathing position) remains identical. In treatment planning for LDR and PDR brachytherapy and for permanent implantation, significant changes may occur by tissue changes (e.g. oedema) which mainly occur during the first day after application. In such cases, images for definitive treatment planning are often taken 24 hours after the application has been performed.

The **standard imaging procedure after application is projection imaging** (radiography) in at least two planes. This allows the 3D reconstruction of the applicator in space, of certain points related to anatomical landmarks, to the GTV/PTV and to critical organs (see physics chapter).

An isocentric radiological device like a simulator with the possibility of fluoroscopic imaging and of taking projection images (film radiographs) is often used. Often some auxiliaries like a box with reference markers are needed (see physics chapter). In this context, the **relevance of sectional imaging after application** and the definitive dose calculation based on this imaging is emphasised. The precondition is the availability of adequate devices for imaging. The applicators used have to be compatible with the corresponding image system and must not lead to major artifacts.

The planning procedure starts with entering all image data into the treatment planning system. The sectional image data may be connected to the data from conventional radiography or may be entered independently.

The main difference to the provisional treatment planning is the definite position of the applicator in, or next to, the target and the organs at risk.

In **radiography assisted definitive treatment planning**, the main objective information is available about the position and geometrical arrangement of the applicator in relation to bony anatomy and sometimes to organs at risk. Therefore, dose distribution is usually calculated according to the applicator geometry and in addition to fixed reference points indicating the target and/or organs at risk. Some dose adaptation is possible in regard to the available imaging information.

In **sectional image assisted treatment planning** the image quality related to the target may be comparable to the provisional planning procedure or maybe inferior, e.g. due to artifacts. The GTV and the PTV are delineated slice by slice as accurately as possible, independent of the position of the applicator. The same procedure is followed for the organs at risk. Image based dose distributions are calculated orientated to the different slice positions or even in 3D with display in systematic or arbitrary planes. For the target and for the different organs at risk dose volume histograms are generated and evaluated (see physics chapter: 2.6, 2.9). Some adaptation ("optimisation") can be done to improve the dose volume relationships, varying the dwell positions and dwell times in stepping source technology or the irradiation times for different catheters for the different active wires (see physics chapter 2.6 and Fig 15.15).

For **all applications, the following parameters are calculated and recorded**: the dimensions (length, width, thickness) and if possible the volumes of the GTV, PTV and the treated volume are stated; the TRAK is recorded; the dose (rate) at specific points is given, indicating the prescription and the reference point, and if possible, indicating the dose in the target and in critical organs.
Dose volume relationships (DVH) for the target and the different organs at risk are recorded, indicating the volumes treated with a certain dose as absolute and as relative values. (for example Fig 5.13, 5.15, 5.16).

For the different methods used in brachytherapy, a number of specific parameters is calculated and recorded.

For interstitial brachytherapy, these parameters are the mean central dose (rate) (MCD), the minimum target dose (rate) (MTD), the homogeneity index, the overdosage volume (150% of MCD), the low dose volume within the PTV (<90%) and the conformity index (treated volume related to PTV) (example Fig 5.4). Further dose volume parameters should be considered, which have been proven to be useful in prostate brachytherapy: D90 (dose that covers 90% of the PTV), V100 (Volume (absolute and relative to the PTV) that receives the prescribed dose), V150 (Volume that receives 150% of the prescribed dose) (Fig 5.13, 5.16).

For intraluminal brachytherapy these parameters are the dose at the reference point and the length of the Reference Volume (RVL); the dose at the applicator/lumen surface (in the central plane/other planes); the overdosage volume with and without the applicator volume (“tissue overdosage volume”); the minimum target dose (if possible), the Treated Volume (if possible) with its dimensions (length, thickness) with and without the applicator (DVH). (see Fig 6.17-20 in reporting chapter; as example for oesophagus Fig 5.9, 24.3, 24.6-10; for bronchus Fig 5.7 26.5).

For intracavitary brachytherapy (uterine cervix and corpus) these parameters are dose (rate) at the prescription and the reference point (e.g. a well defined point A or point My (corpus)); dose (rate) at additional reference points (bony landmarks, organs at risk like rectum, bladder (14) and vagina); the dimensions and the volume of the Treated Volume (with and without the applicator and in relation to the applicator); the 60 Gy reference volume, the dimensions and the volume of the isodose going through point A (example cervix, see Fig 6.28 and 14.16; example endometrium,
see Fig 15.10). The D90 (dose that covers 90% of the PTV) and the V100 (Volume that receives the prescribed dose) can also be given (Fig. 5.15, 14.14).

Fig 5.14: CT based 3D planning for intraluminal oesophageal brachytherapy with a 15 mm diameter applicator with delineation of the luminal surface and the outer contour of the oesophageal wall/GTV on transverse CT images. Thickness of the oesophageal wall with the applicator in place is from 3-8 mm. 3D reconstruction of the applicator is shown together with isodose levels in the coronal and sagittal plane. Dose level of 6 Gy is prescribed at 7 mm into the oesophageal wall, resulting in 12 Gy at the luminal surface. Reference dose at 5 mm is 8 Gy. (level 2)

In combination treatment with external radiotherapy the respective parameters must be given for both modalities: at the ICRU point for external beam therapy, at specific reference points for brachytherapy. As image matching between brachytherapy and external beam therapy is hardly feasible at present, the respective parameters are usually added taking into account the various biological effects of different dose rates and different doses per fraction.
As at present, little is known about the correlation between certain dose volume relationships based on 3D sectional imaging with regard to treatment outcome and treatment-related morbidity, this data must be carefully collected for later correlation to clinical outcome.

Fig 5.15: MRI based 3D definitive treatment planning (A) for a combined intracavitary and interstitial gynaecological brachytherapy in a large III B cervix cancer with insufficient remission after 45 Gy pelvic EBT combined with cis-platin chemotherapy. Provisional treatment planning for needle placement was done based on the first intracavitary application with MRI and the ring applicator in place. At the time of brachytherapy the maximum latero-lateral dimension of the GTV was 6.5 cm, with 4.5 cm to the right from the uterine canal. Maximum thickness was 5 cm, maximum height 5 cm. Four round plastic needles were introduced through the vagina in template assisted free hand technique into the macroscopic tumour on the right side parallel to the intrauterine tube with the cervix ring applicator in place using a small template adapted to the ring. The treated volume (85 Gy (biologically weighted dose) corresponding to the “500 cGy-isodose”) is 140 cm³ and encompasses the large GTV at the time of brachytherapy (60 cm³) and the initial GTV (85 cm³) tightly. The isodose indicating the 60 Gy reference volume is also shown (“280 cGy-isodose”). Maximum width is 9 cm, thickness 7.5 cm, height 9 cm (reference volume is 440 cm³). No significant overdose at the rectum, sigma or bladder was observed: the 2/5cm³ values for the rectum, bladder as calculated from DVH (B) were 50%/60%, 60%/70% of the prescribed dose for brachytherapy, which corresponds to a total biologically weighted dose of 60-70 Gy (level 3); DVH for the GTV is also shown (C).
6 Image Assisted Quality Control of Dose Delivery

In certain situations it seems to be advantageous to control and verify the applicator position related to the target and to organs at risk during or after brachytherapy. This can be done in principle by any imaging method available, as far as the patient with the applicator or the radioactive sources can be examined and taken to the respective imaging device (in contrast to external beam therapy). Usually, the imaging method chosen is the one used for definitive treatment planning.

Fig 5.16: Prostate Cancer: Image assisted quality control of dose distribution in a patient after iodine seed implantation (compare Fig 5.5 and 13: identical patient): pelvic X-ray (A) and transverse MRI (B) with delineation of the PTV, the urethra and rectum on the MRI and isodose lines based on 3D dose calculation. The post planning DVH (C) indicates that 93% of the PTV is enclosed by the prescribed dose (140 Gy) ("V100") (a), about 5% of the delineated rectal wall (<1cm³) receive more than 110 Gy (b), and less than 5% of the prostatic urethra receive more than 250 Gy. Compared to the DVH taken from the on line definitive treatment planning based on ultrasound, there is a slight decrease in PTV coverage ("V100"), a similar dose volume relation for the rectum, and a slight increase in the volume of the urethra that receives 250 Gy. (level 2/3) (compare 5.13B).
Image assisted quality control of dose delivery is performed in LDR or PDR brachytherapy by taking radiographs (alternatively CT/US/MRI) during the course of brachytherapy for comparison with the images for definitive treatment planning. Such quality control is advisable, if there is the possibility of an applicator movement (e.g. duration of brachytherapy over a long period of time) or a clinical suggestion of an applicator movement which may have a significant impact on dose distribution.

In HDR brachytherapy, quality control of an application is only possible after irradiation has been performed.

In prostate brachytherapy (permanent seed implantation) a regular check by radiographs is taken to control the number and distribution of active seeds. Final dosimetry for iodine prostate brachytherapy is traditionally based on radiographs, US, CT or MRI taken 4-6 weeks after application (Fig 5.16).

7 Different Levels of Dose and Volume Reporting in Image Assisted Brachytherapy

Analogue to the concepts as outlined in ICRU report 50, 58, 62 (15,16,17), it seems to be advisable to use the three levels for dose and volume reporting and classification of dose level and volume reporting for the whole field of brachytherapy with regard to imaging (26) (compare chapter 6.1 (reporting in brachytherapy)).

The place of imaging in brachytherapy is only comprehensively settled with regard to projection imaging (radiography), which is referred to as level 1 (basic and advanced), where at least minimum requirements for brachytherapy reporting are fulfilled.

Sectional image based reporting providing more complete and relevant information is referred to as level 2. Reporting based on full 3D sectional image based 3D data acquisition and 3D dose calculation is referred to as level 3, indicating the level of research and development.

Level 1: dose and volume reporting according to radiography assisted standardised and individualised determination of dose distribution (through basic and advanced radiographic techniques)

Basic Level 1: dose and volume reporting according to radiography assisted standardised determination of dose distribution related to the applicator geometry and only partly to patient topography

Planning and performance of brachytherapy according to basic level 1 is to be assumed, if there is a standard application (applicator) with a fixed geometry, a documentation by radiographs, and an unambiguous, reproducible definition of a reference point or a reference system related to the geometry of the application. Standard variations are possible in regard to length, width and thickness of the reference isodose, which results in variations of treatment time. Dose distributions are available as an atlas of isodose distributions for a given application geometry or as a standard programme for a certain application geometry within a computer assisted treatment planning system which is adjustable within certain limits. Radiography serves as a documentation of the application in relation to bony and soft tissue anatomy as far as represented on such radiographs. Furthermore, it enables a check of the position of the applicator and a global estimate of the dose distribution related to the applicator and the visible radiographic anatomy, e.g. by superimposition of the dose distribution onto the radiograph.
Basic Level 1 is applicable for one catheter intraluminal applications (oesophagus, bronchus),
standard intracavitary applications (uterine cervix and postoperative brachytherapy of the vaginal
cuff) and standard interstitial brachytherapy with fixed geometry (e.g. needles with fixed geometry in
breast and head and neck brachytherapy).

Reference points are defined in *intraluminal brachytherapy* at a given distance from the applicator
surface and at the applicator surface with standard applicator diameters in the central plane: at a
reference distance of 5 mm from the applicator surface in all but intravascular applicators
(oesophagus, bronchus, vagina, bile duct); at 1 or 2 mm from the vessel wall/applicator surface in
intravascular brachytherapy (coronary or peripheral arteries). In intravaginal applications an
additional lateral projection image enables a rough estimate of the dose at bladder and rectum and
checking the position of dosimetric probes, if inserted.

In *interstitial brachytherapy*, the mean central dose (MCD) is calculated and the minimum target dose
is given in a certain relation to the MCD (e.g. 85%). If necessary, standard volumes can also be
given for a certain application, such as for example the treated volume, the overdosage volume, the
low dose volume or a certain reference volume for a fixed dose.

In *intracavitary brachytherapy* projection images, which are taken in the anterior-posterior and lateral
direction serve for checking and documentation of the adequate position of the applicator. A
reference point and other dose points can be drawn onto these projection images. In intracavitary
cervix brachytherapy, point A is defined as a reference point (e.g. related to the cranial surface of the
ovoids or the ring). Dimensions of the target and the treated volume can also be delineated.

In general in basic Level 1, dose calculation is performed based on standard programmes in the
respective Treatment Planning System or the isodose atlas and is not based on data entry from
projection images accurately representing the individual situation in the patient. Therefore, dose and
volume reporting in basic Level 1 is related to the standards for the respective applicator: no precise
correlation exists between the reported dose at the dose points and the actual dose at these dose
points within the individual anatomy as demonstrated on the projection images.

**Advanced Level 1: Dose and volume reporting according to radiography assisted
individualised dose and volume determination correlated to the individual topography in the
patient as presented on radiography**

The term “*Advanced Level 1*” is introduced for dose and volume reporting in brachytherapy if dose
distribution is precisely correlated to the individual topography as represented on two radiographs
with the applicator in place. Precondition is the data entry of individual applications and of individual
dimensions (target and organs at risk) through projection images into the Treatment Planning
System. Consequently, different dose points and volumes are calculated and referred to the
dimensions of the target and organs at risk, all based on the delineation of these in the projection
images.

Typical examples are intracavitary brachytherapy in the uterine cervix and corpus, interstitial
brachytherapy (needles, flexible tubes) and intraluminal applications with one or more flexible
catheter(s) (bronchus, bile duct).

If treatment planning is performed according to advanced Level 1, the projection images, which must
be taken in a defined geometry, serve as a basis for dose calculation. The applicator, the dose points
related to the applicator and to the individual anatomy of the patient, including the position of organs
at risk, are to be precisely indicated. All these points are reconstructed in three dimensions and the
dose is 3D-calculated. The calculated dose at dose points corresponds to the dose at these points in
the patient as documented on the radiographs.
Based on the data entry into the Treatment Planning System, doses at points can be adapted to the individual situation. This adaptation corresponds to the points in the patient as documented on the radiographs.

"Level 2": Dose and volume reporting according to sectional image assisted individualised dose and volume determination correlated to the individual topography in the patient as presented on one or multiple sectional images (2D)

Dose and volume reporting in brachytherapy according to level 2 is given, if dose distribution is precisely correlated to the individual topography, the target and the organs at risk as represented on one or multiple sectional images with the applicator in place. By sectional images taken with the applicator in place, an accurate assessment of configuration and topography of the application in relation to target and organs at risk can be achieved. The applicator, GTV and PTV are delineated on the different image slices as well as the contours of organs at risk. Precondition is the entry of the sectional images into the Treatment Planning System. Computer assisted dose calculations are performed in 3D for the different images. In addition to dose points given in level 1, these calculations allow an estimate of the dose distribution in the target volume, an estimate of the minimum target dose (treated volume), and of the dose distribution related to organs at risk. As only a limited number of sectional images are taken, there is no complete representation of the target volume or the volume of organs at risk in these dose volume relationships.

The classical example for this approach is treatment planning in prostate cancer brachytherapy, based on 7-11 transverse sectional images taken with the endorectal ultrasound probe reproducibly advanced by a stepper unit. For classical brachytherapy sites such as gynaecology and head and neck, anecdotal reports using such approach are available in literature (7,11,18,28,30).

"Level 3" Dose and volume reporting according to sectional image assisted individualised dose and volume determination correlated to the individual topography in the patient as recorded by a 3D examination

Dose and volume reporting in brachytherapy according to level 3 is given if dose distribution is precisely correlated to the individual topography as represented on a 3D examination, including the applicator, target and organs at risk. This includes an individualised 3D-computer assisted assessment of the anatomy based on 3D sectional imaging (CT, US, MRI) and 3D dose calculations within this 3D anatomy. The GTV and PTV, the applicator, organs at risk and respective volumes (points) are considered in detail in this procedure. Precondition is the entry of the whole 3D data set into the Treatment Planning System. Based on 3D dose calculations, DVH for the target volume is available as well as DVHs for organs at risk. In addition dose at reference points can be indicated and displayed in three dimensions. Any volumes of interest can be identified in 3D. Structure specific dose-volume histograms become also available as a tool for treatment planning, for example natural DVH (see in detail physics chapter).

One typical example for such a procedure is stereotactic interstitial brachytherapy in brain tumours based on 3D-CT or MRI. Some experience is also reported for gynaecology (5,7,10,12,18,24,28,30,29,34) and head and neck (11). In prostate brachytherapy this tool is recently becoming available with the integration of 3D ultrasound into 3D treatment planning (2,4,6,19,21,23,31,32).

As sectional imaging is superior to projection imaging, efforts are being made to fully integrate sectional imaging into standard clinical brachytherapy treatment planning (level 2, level 3) - as is already common practice in treatment planning of external radiotherapy today.
Essential issues for the further development of modern image based brachytherapy is the availability of image hardware, the adaptation of image hardware and software to the needs of brachytherapy procedures, the development of software for interactive image guidance, the development of specific image compatible applicators, the integration of applicators into 3D navigation systems, and the connection of image devices via networking to treatment planning computers.

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