



GEC-ESTRO Recommendations

Recommendations from Gynaecological (GYN) GEC-ESTRO Working Group: Considerations and pitfalls in commissioning and applicator reconstruction in 3D image-based treatment planning of cervix cancer brachytherapy

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ABSTRACT

Image-guided brachytherapy in cervical cancer is increasingly replacing X-ray based dose planning. In image-guided brachytherapy the geometry of the applicator is extracted from the patient 3D images and introduced into the treatment planning system; a process referred to as applicator reconstruction. Due to the steep brachytherapy dose gradients, reconstruction errors can lead to major dose deviations in target and organs at risk. Appropriate applicator commissioning and reconstruction methods must be implemented in order to minimise uncertainties and to avoid accidental errors.

Applicator commissioning verifies the location of source positions in relation to the applicator by using auto-radiography and imaging. Sectional imaging can be utilised in the process, with CT imaging being the optimal modality. The results from the commissioning process can be stored as library applicators. The importance of proper commissioning is underlined by the fact that errors in library files result in systematic errors for clinical treatment plans.

While the source channel is well visualised in CT images, applicator reconstruction is more challenging when using MR images. Availability of commercial dummy sources for MRI is limited, and image artifacts may occur with titanium applicators. The choice of MR sequence is essential for optimal visualisation of the applicator. Para-transverse imaging (oriented according to the applicator) with small slice thickness (≤ 5 mm) is recommended or alternatively 3D MR sequences with isotropic voxel sizes. Preferably, contouring and reconstruction should be performed in the same image series in order to avoid fusion uncertainties.

Clear and correct strategies for the applicator reconstruction will ensure that reconstruction uncertainties have limited impact on the delivered dose. Under well-controlled circumstances the reconstruction uncertainties are in general smaller than other brachytherapy uncertainties such as contouring and organ movement.

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Traditionally, evaluation of a brachytherapy implant has been based on a pair of X-ray images [1,2] whereas dose calculations based upon sectional imaging (CT, MRI, and US) have played a minor role in brachytherapy, as opposed to external beam radiotherapy. However, during recent years 3D image-guided brachytherapy has been introduced into clinical practice worldwide enabling conformation of the dose distribution to the target volume and avoidance of a high dose to organs at risk (OAR) [3–9]. Calculation of the dose

to anatomical structures requires that the geometry of the applicator and the source dwell positions are extracted from the images and imported into the treatment planning system (TPS); a process often referred to as applicator reconstruction. Inaccuracy in this process can lead to geometrical uncertainties and thus uncertainties in the definition of source positions. These uncertainties influence the accuracy of the delivered dose to both target volumes and organs at risk. It is therefore important to include the considerations of the reconstruction process when evaluating uncertainties for 3D image-based treatment planning in brachytherapy.

In 2000 GEC-ESTRO established a Gynaecological Working Group (GWG) with physicians and physicists from different centres

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actively involved in brachytherapy using 3D image-based treatment planning. Their task was to describe and develop basic concepts that would enable the various groups working in this field to use a common language for appropriately communicating their results. The GWG has published several recommendations and results from scientific projects [3,4,9]. In May 2005 the group was extended and the European Network for 3D Gynaecological Brachytherapy was established. Within the frame of this network several projects were defined, one of them named "Applicator reconstruction". The aim of this reconstruction project was two-fold; (1) to describe the practical methods for applicator reconstruction (including commissioning) and to identify the crucial points in the reconstruction process and (2) to evaluate the dosimetric uncertainties related to geometrical uncertainties. This paper will report the results of point (1). The results of point (2) have been published elsewhere [10,11].

Commissioning of applicators

When introducing a new applicator in the clinic, the commissioning process is important. This process includes the verification of the location of clinically relevant source positions in relation to the outer surface of the applicator and/or in relation to reference points in the applicator. The commissioning could for example include determination of the distance from the tip of a tandem applicator or a needle to the first dwell position. Determination of the distance from the top of a ring applicator to the level of the source path is another example. This parameter is necessary for the localisation of point A in relation to the applicator (Fig. 1).

Traditionally the commissioning has been performed using X-ray images [12]. However, with rigid applicators sectional

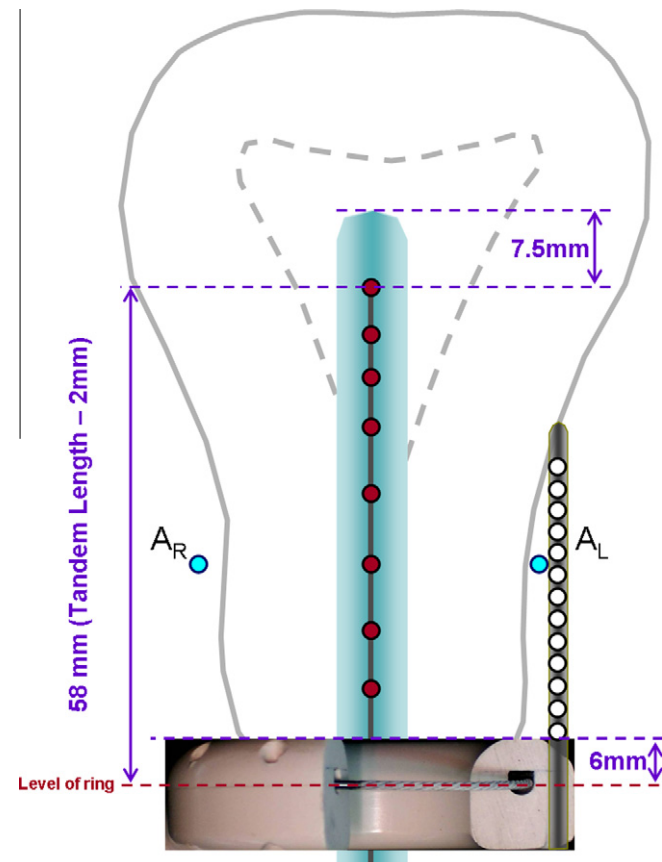


Fig. 1. Indications of dimensions of ring and tandem applicators determined during commissioning.

imaging can also be utilised in the process, with CT imaging being the optimal modality. During the commissioning the applicators should then be positioned on the CT table in such a way that the relevant part of the applicator can be visualised in one image. Fig. 2a shows a CT image of a ring applicator where the lumen of the ring is fully visualised. Users should explore methods for digitisation in order to be able to localise the correct source positions inside their own applicators. In Fig. 2b two reconstructed applicators are shown based on the CT image in Fig. 2a. For both the reconstructed applicators the digitisation started at the same point (first marker), but two different tracks were digitised (indicated in Fig. 2a): (1) through the centre of the source channel and (2) close to the inner surface of the source channel. The reconstructed applicators are loaded with the same source configuration and from these two images it is obvious that there is a deviation between source positions in track 1 and 2. Consequently the calculated dose distribution around the applicators will be different. The correct method of reconstruction should be verified using auto-radiographs [12] from which the true location of the dwell positions is found. In Fig. 2c an example of an auto-radiograph is shown. For this auto-radiograph the ring applicator and the source configuration from Fig. 2a and b are used and it seems that track 1 is more correct.

Extra care should be taken using curved applicators, e.g. the ring applicator or ovoids. Inside a curved applicator the source attached to a drive cable will be pushed towards the outer wall of the applicator [13]. When the source moves inside a curved applicator, this effect may lead to a non-circular track of the source and an offset in source position compared to source movement in a straight applicator. This is very well demonstrated in a study by Kohr and Siebert [14]. As illustrated by Thomadsen [12] in Fig. 9.5 of his book chapter "Quality management for dosimetric treatment planning", this effect can also lead to a discrepancy between the position of the marker on a markerstring and the true source position. Hellebust et al. performed a comparison of markerstring and true source position by imaging the ring applicator with the source inside using CT [10]. They found a deviation of 2.5 mm between the dwell position and the corresponding marker in the posterior part of the ring, which is most probably due to the curvature of the applicator. For afterloaders which are extending the source to the distal end of the applicator tube before starting source retraction (e.g. GammaMed, Varian), the first millimeters of cable retraction will just straighten the wire without leading to any physical retraction of the source (slack of the source cable). If no correction is applied, this will lead to a systematic misplacement of all source positions in the ring. However, compensation can be performed by applying an offset and defining the end of the source channel beyond the real end of the source channel by 2–3.5 mm (see Supplementary data). The offset is dependent on the type of ring and may even change slightly with source exchange.

When using titanium applicators and MR image guidance, additional phantom MRI scans have to be performed for applicator commissioning. Although the titanium material is MRI compatible it introduces susceptibility artifacts in the images [15]. The artifacts are dependent on image sequence, and therefore MRI phantom scanning should be performed with the sequences used for clinical purpose. By fusing MRI and CT phantom scans the position of the MR image artifacts can be assessed with regard to the applicator geometry as visualised on CT imaging (Fig. 3).

From the results of the applicator commissioning the geometry of the applicator, or more correctly the source track in relation to the applicator, can be stored as library files and later used clinically. Since errors in the library files will lead to systematic errors for clinical treatment plans, it is crucial that special care is undertaken to perform the commissioning properly. For other general aspects of the applicator commissioning and acceptance test the

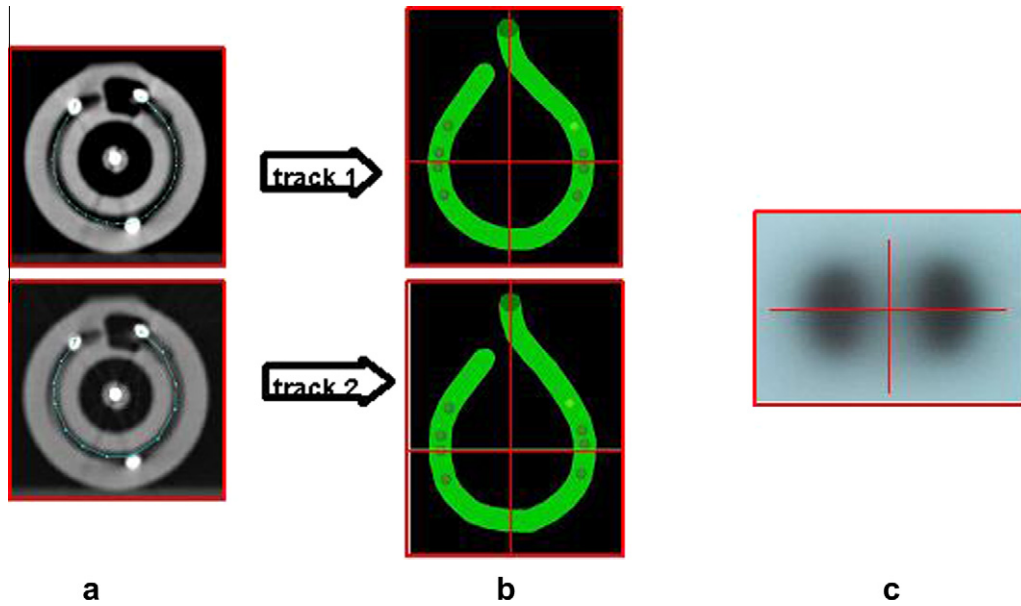


Fig. 2. (a) The same CT image is used for ring applicator reconstruction using two different digitisation tracks indicated by the dotted lines, (b) the resulting reconstructed applicators with the same source configuration, (c) auto-radiograph of the same applicator as in (a) with the same source configuration as in (b).

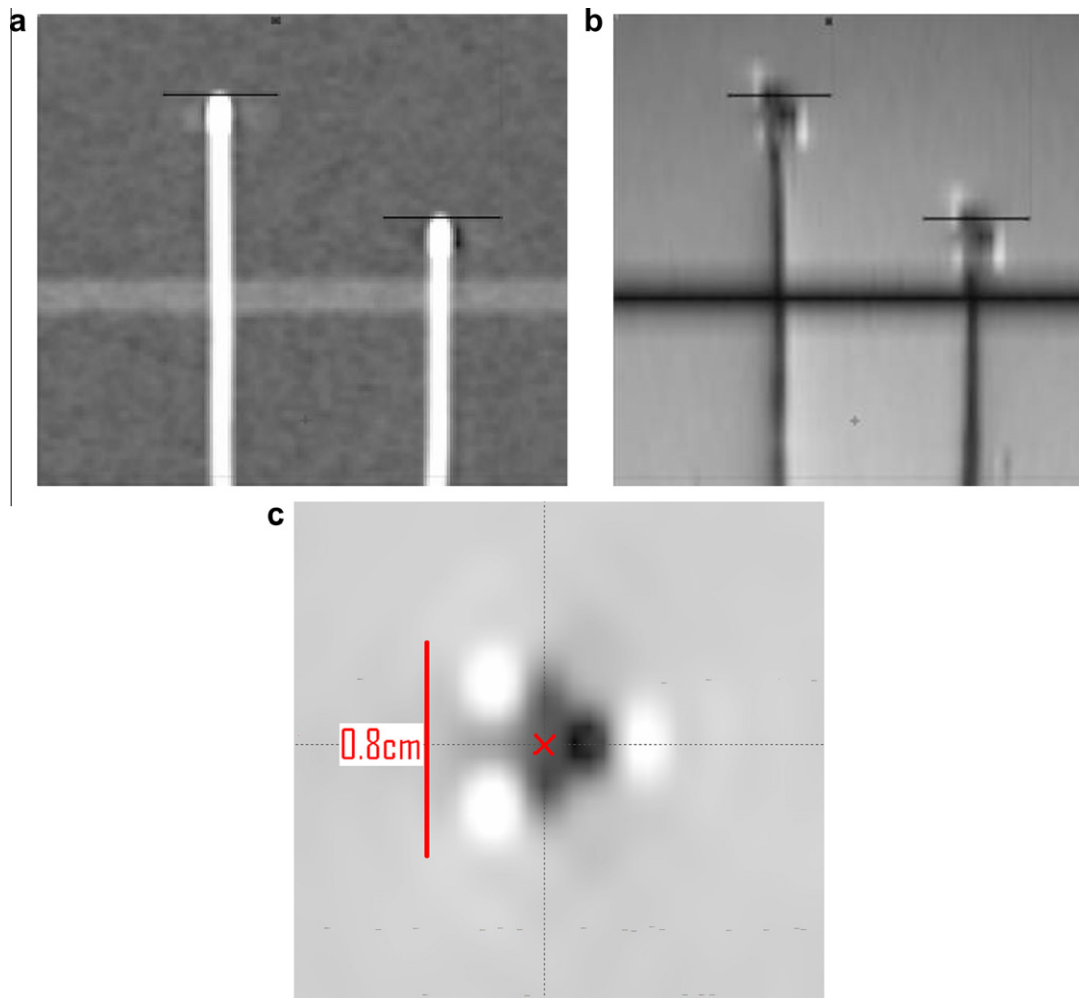


Fig. 3. Coronal reconstruction of transverse CT scan (a) and T2-weighted MR scan (b) of a water phantom with titanium needles. MRI susceptibility artifacts are seen in relation to the needle tip. (c) Para-transaxial alignment of the tandem applicator on MRI. Bright susceptibility artifacts are seen around the tandem. The red X marks the position of the centre of the source channel.

reader is referred to ESTRO booklet No. 8 [16] on quality control of brachytherapy equipment.

The reconstruction process

To be able to describe and analyze the reconstruction procedure properly the process can be divided into two steps: (1) reconstruction of the applicator geometry and (2) merging of applicator and anatomical geometries. The first step includes the process of defining the source path by positioning dwell positions in relation to each other or in relation to reference points in the applicator. The second step is the process where the source path is positioned in the 3D study, in relation to the anatomy of the patient. Obviously both steps are equally important, since a correctly reconstructed applicator positioned wrongly in the 3D study would lead to incorrect calculation of the dose distribution in the patient.

The reconstruction of the applicator (step 1) can be performed by different methods: library plans (LIB), direct reconstruction (DR) or a combination of these two methods. The LIB method is only possible with rigid applicators. Both the methods are encumbered by uncertainties that should be taken into account in the treatment planning procedure.

When the LIB method is used, a pre-defined library file with the source path geometry is used and imported into the clinical image set. The procedure for importing these library files is critical. One approach to merge the coordinate system of the library file with the coordinate system of the clinical 3D study is to identify at least three points in both coordinate systems. Well-defined points in the applicator could be used, i.e. markers on the markerstring, tip of the applicator or holes for needles. In one of the treatment planning systems used within the GYN GEC-ESTRO network (Plato, Nucletron B.V., Veenendaal), these points used for back projection of library files can only be defined in the original images and not in the reconstructed images. If a coronal view from the CT shows that some of the points are located between the CT slices, the merge will not be entirely correct. Another approach which is allowed in some treatment planning systems is to rotate and translate the pre-defined library applicator until it fits the clinical 3D study. When using several rigid applicators each applicator should be imported separately, since there is a risk that the position of the applicators in relation to each other could change inside the patient.

Using the DR method the applicator is reconstructed by digitising the track of the source directly in the acquired images. With this method it is important to correctly identify the first dwell position, either by specifying this position relative to a reference point in the applicator (e.g. tip of the applicator) or by identifying the first marker on the marker string. When transversal (or para-transversal) images are used, a lateral or frontal view is a valuable tool to determine whether a reference point or the first marker is located between two images. When the first dwell position is identified the track of the source has to be digitised and the procedure elaborated during the applicator commissioning should be used. When a curved applicator (e.g. the ring applicator) is digitised in several images there is an inherent risk of reconstructing too long or too short a track and the reconstructed applicator may emerge jagged. Consequently the dwell positions will be located wrongly resulting in inaccuracies in the dose distribution. Fig. 4 shows an example where a ring applicator set is directly reconstructed based upon CT images with 3 mm slice thickness. The jagged nature of the ring applicator is clear in the sagittal plane and the position of the sources in relation to each other along the z-axis (along the uterine applicator) will not be correct. However, the uncertainties could be minimised by trying to achieve correct x- and y-coordinates by using the results from the applicator commissioning, i.e. the transversal view in Figs. 2 and 4 should appear the same.

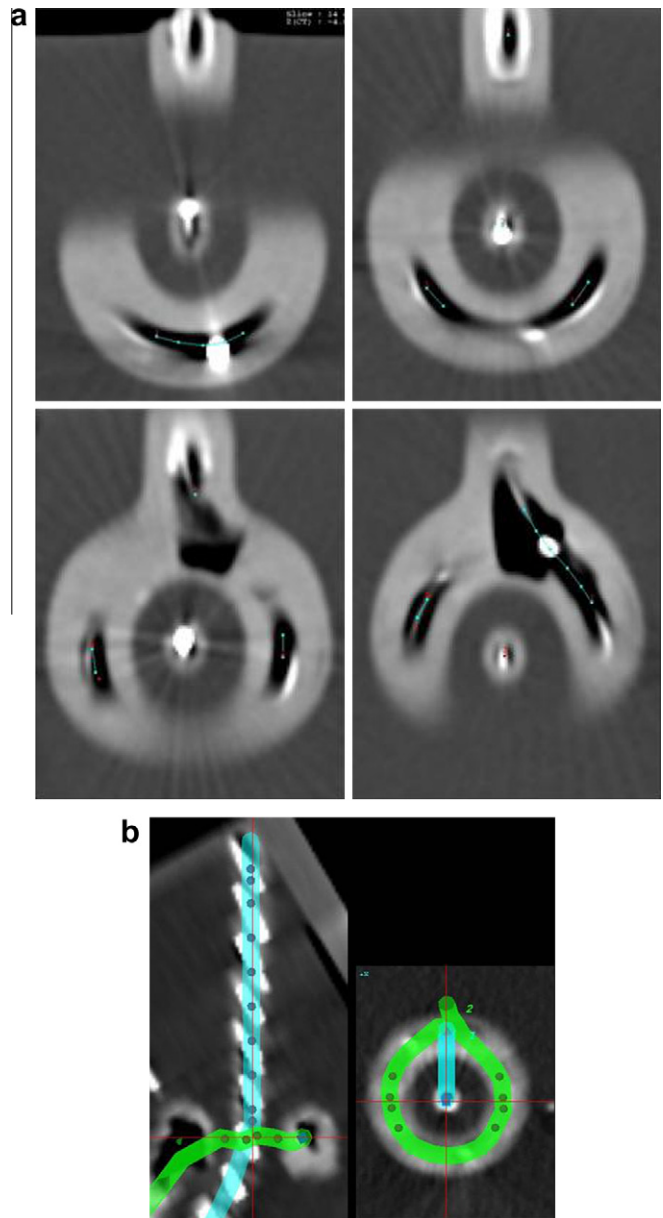


Fig. 4. (a) Transversal images of a ring tandem applicator set with the ring visible in several slices, (b) reconstructed applicator using the DR method in para-sagittal (left) and para-transversal view (right).

Most treatment planning systems currently facilitate multiplanar reconstructed (MPR) images. Thus, images can be reconstructed to visualise the relevant parts of the source channel in one image and the problem described above will be eliminated. The quality of these MPR images depends on the distance between the original images. Usually it is impossible to visualise the relevant parts of all the applicators in one MPR image. One set of MPR images should then be reconstructed for each of the source channels. Since the quality of the MPR images is sometimes a limitation, the reconstruction of straight, rigid applicators should preferably be performed by using the DR method. To avoid a jagged reconstructed applicator [17] only two points should be used if a straight and rigid applicator is being reconstructed.

Using the DR method a verification of the reconstruction can be performed by loading a standardized source configuration (according to the ring diameter/ovoid size) into the reconstructed applicator. The standardized loading should result in a source configuration corresponding to what was found during commis-

sioning – if this is not the case there may be a geometrical error in the applicator reconstruction. Furthermore, the standard dwell times and corresponding point A doses could be tabulated (including an estimate of the uncertainty), so that it can be checked that, for any reconstruction, dwell times and point A dose fit together. This latter procedure will be an extra confirmation of correct geometrical applicator reconstruction and correct positioning of point A.

Applicator reconstruction using CT images

It is easy to visualise the track of the source in CT images as illustrated in Figs. 2 and 4. Often the lumen of the applicator is well visualised and this means that a markerstring is not always necessary. Some X-ray catheters may produce artifacts in the CT images resulting in larger uncertainties in the reconstruction and contouring process.

Usually the CT scan is performed without a tilt of the CT gantry, and slice thickness ≤ 3 mm is recommended to give the best visualisation. The lumen of the ring will be visible in several slices, e.g. 3–4 images for 3 mm slice thickness (Fig. 4). In order to visualise the ring in one image a multiplanar reconstructed image through the ring can be used. The reconstructed image can be used during direct reconstruction or for positioning of a library applicator. Hellebust et al. analyzed the impact of the applicator orientation and the reconstruction method used on the calculated dose around a reconstructed ring applicator set using CT imaging [10]. Their results showed that it was not possible to identify one applicator orientation that gave lower uncertainties with regard to the calculated dose around the applicator. Moreover they found that the LIB reconstruction method gave smaller standard deviations than the DR method looking at the data for all the applicator orientations, i.e. without standardizing the applicator orientation the LIB method was most accurate. However, all orientations and all reconstruction methods resulted in limited variation in calculated dose, i.e. both LIB and DR are feasible for applicator reconstruction in CT images [10].

Applicator reconstruction using MR images

GEC-ESTRO guidelines recommend T2-weighted MR images for target and OAR delineation [3,4]. Preferably, contouring and reconstruction should be performed in the same image series in order to avoid fusion uncertainties and patient/organ movement in between different image acquisitions. Choice of MRI sequence is important for the accuracy of applicator reconstruction. Para-transverse imaging is recommended when the TPS accepts this because: (1) the applicator is better visualised in para-transverse than in transverse images and (2) para-transversal images are preferred for contouring [18]. In general, a small slice thickness is recommended although long acquisition times should be avoided in order to avoid patient movement during image acquisition. 3D sequences with isotropic voxel sizes produce an excellent visualisation of the applicator, and it is also possible to do contouring in certain T2-weighted 3D sequences [19]. Slice thickness should under all circumstances not be larger than 5 mm. However, even with slice thickness around 3–5 mm, visualisation of the applicator can be difficult or inaccurate with T2-weighted images, specifically in implants including needles. Therefore, in some situations, it can be an option to acquire CT images or additional MRI sequences in order to increase the reconstruction accuracy or to aid and streamline the reconstruction process in general. The applicator reconstruction can then be performed in an image set having superior applicator/source channels visualisation as compared to T2-weighted transversal MR images, e.g. CT images, sagittal/coronal MRI, T1-weighted MRI, 3D MRI acquisitions or X-ray images [20,21].

With MR images the lumen of the applicator is not visualised, since air and applicator material do not give any signal. Moreover, conventional markers used for X-ray and CT are not compatible with MRI and cannot provide visualisation of the source path. At present there are only few commercially available marker strings for T2 MR images. Catheters containing CuSO_4 solution [20,22], water [23], or glycerin [24] can be used in plastic applicators (Fig. 5). However, many commercially available applicators have a narrow entrance diameter which limits the volume of the fluid and the signal from these marker strings may be weak in T2-weighted MR images. Reference structures such as cavities filled with fluid (Fig. 6) or needle holes [13] can be used as long as the location related to the dwell positions is known. In titanium applicators fluid contrast cannot be visualised inside the source guide tubes due to susceptibility artifacts [20].

A plastic applicator appears as a black area in the MR images, representing the physical dimensions of the applicator and not the source path. Alternatively, to direct visualisation of the source path, applicator reconstruction can be based on using the outer applicator surface to guide the positioning of the source path. In this case the knowledge of applicator and source path geometry obtained during applicator commissioning is used, e.g. the distance between the surface of the applicator and the first dwell position, and the thickness of material above the vaginal sources. As some TPSs contain an applicator library which includes information about the physical outer applicator dimensions, an applicator file can be imported and rotated and translated until it matches the black area in the patient MR images (Fig. 7). This procedure is fast, simple, and less prone to reconstruction errors. There will be a reduced risk of introducing incorrect applicator geometry (such as wrong ring diameter or ovoid size), because visual verification of the applicator reconstruction can be done directly by assessing whether the black applicator void fits with the applicator shape.

When using MR imaging for applicator reconstruction it is important to be aware of the magnitude of geometrical distortion. The region of interest in gynaecological brachytherapy is located centrally in the patient where the geometrical distortion is considered to be small (<2 mm) when appropriate MR sequences are applied, as well as distortion correction algorithms provided by MR machines manufacturers [25].

Merging/using/fusing several image sets

When supplementary imaging (e.g. CT, additional MRI or X-ray) is done to aid the reconstruction procedure the two image sets used for contouring and reconstruction have to be co-registered. Either the applicator geometry is fused into the T2-weighted images, or the contours are copied and pasted into the image sequence which contains the applicator reconstruction. It is essential that the registration is performed with the aim of matching the applicator and not for instance bony structures. Fusion uncertainties will result in corresponding misplacement of the applicators and corresponding dose calculation uncertainties. It should always be considered whether the fusion uncertainties are larger than the reconstruction uncertainties would be if the reconstruction was performed directly on image series where the delineation is performed.

Furthermore, the procedure should consider uncertainties due to the artifact shifts that change with pulse sequence. When using metallic applicators in particular, care should be taken to verify that the applicator artifacts are positioned correctly with regard to the applicator geometry.

Examples of reconstruction procedures

As indicated above there are many different approaches to 3D image-based applicator reconstruction. A survey distributed to

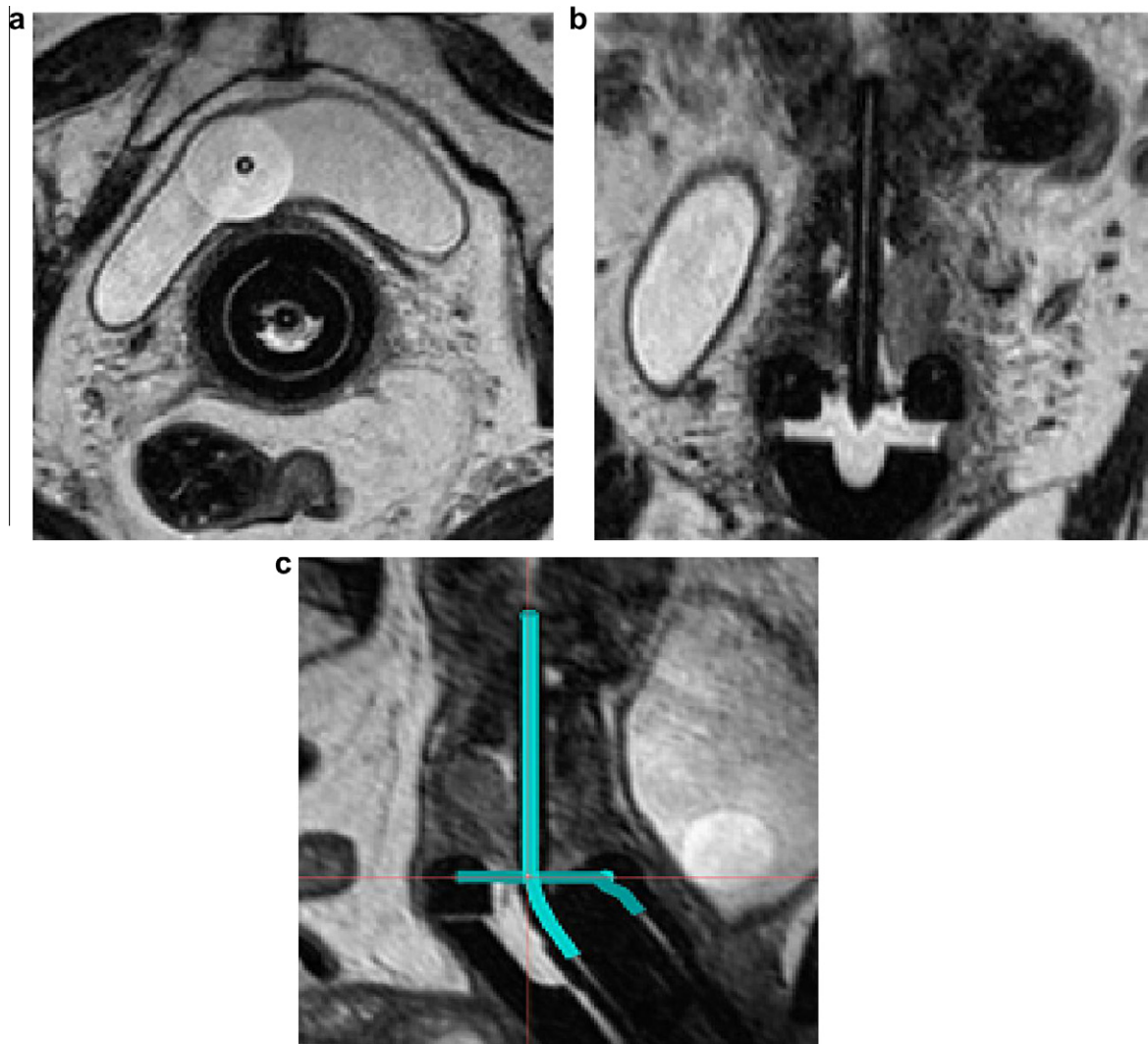


Fig. 5. Reconstruction of plastic applicator in a 3D MR study (SPACE sequence). Plastic catheters with fluid extracted from MR skin markers (MR-SPOTS[®] Beekley) are inserted into the ring and tandem applicators. (a) Para-transverse image at the level of the ring channel, (b) Para-coronal image and (c) Para-sagittal image with a reconstructed tandem and ring applicators. The signal void from the catheter in the ring and tandem guide tubes can be seen in the vagina. By rotating the library applicator correctly with regard to these source guide tubes, the rotation of the ring will become correct.

seven European centres with substantial experience in CT or MR-based gynaecological brachytherapy revealed that applicator reconstruction was performed using six different procedures. The procedures were closely related to the possibilities in the treatment planning system, the image modality available and the type of applicator used. A comprehensive description of different reconstruction procedures is given in Supplementary data together with a consensus data set of dimensions of the different applicators. It is emphasized that every department has to characterise their applicators as a part of their own applicator commissioning procedure (see above). Supplementary data should only be used as reference values.

Discussion

The brachytherapy dose gradient in an intracavitary application is typically in the range of 5–12% per mm at distances of 1–3 cm from the source channels. Geometrical uncertainties will affect the dose according to this dose gradient, and even relatively small geometric errors may have a critical effect on the dose to tumour or organs at risk. In clinical routine there are several sources of geometrical uncertainties such as source positioning (afterloader per-

formance), applicator reconstruction, applicator displacement and organ movement. Applicator reconstruction inter-observer variation has been reported to be less than 0.5–1 mm (1 standard deviation) [20] when appropriate reconstruction methods are implemented in accordance with the GEC-ESTRO recommendations described in this paper. Such reconstruction uncertainties are smaller than inter-observer contouring uncertainties which have been reported to be of the order of 2 mm (1 standard deviation) [18]. Organ movement or applicator displacement in between imaging and treatment lead to discrepancies between calculated and delivered dose. Organ motion has been shown to have more impact on DVH parameters than reconstruction uncertainties [21].

The consequence of reconstruction errors depends on the direction of the error and the organ looked at. Rectum and bladder have been reported to be the most sensitive organs towards reconstruction uncertainties [11]. D_{2cc} changed by on average 5–6% per mm of applicator reconstruction error in anterior–posterior direction and up to 7% in single patients. For other directions and for HR-CTV (D90, D100) and sigmoid (D_{2cc}), the average changes were below 4% per mm although individual patients showed changes up to 5% per mm of reconstruction error.

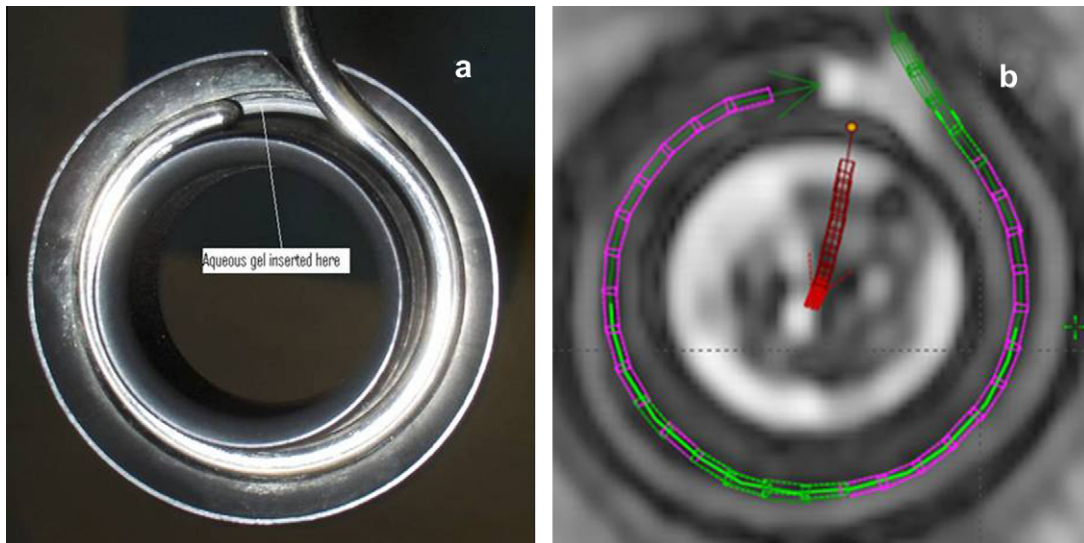


Fig. 6. Reconstruction of titanium ring applicator in MR images. (a) Placement of aqueous gel at the end of the ring channel before assembly of the ring cap. (b) Rotation of the reconstructed ring according to the position of the signal from the aqueous gel.

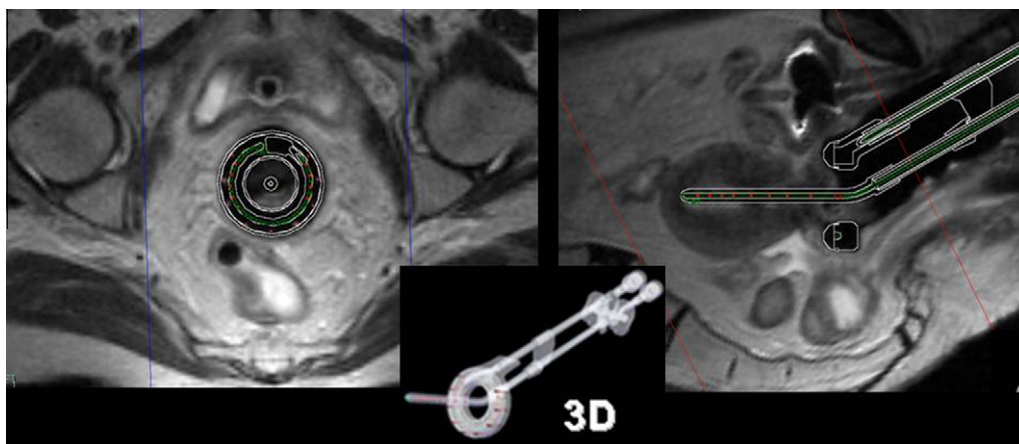


Fig. 7. Position of a library applicator (in the middle) in the transversal (left) and sagittal (right) plane.

With CT-based reconstruction the visibility of the applicator is usually excellent and it has been shown that the dose variation between different CT reconstruction methods is limited – below 4% (1 standard deviation) in clinically relevant dose points [10]. Even with MRI-based reconstruction, the variations between different reconstruction methods as well as inter-observer variations have been reported to be limited – less than 3–6% in relevant DVH parameters of target and OARs (HR-CTV D90, OAR D_{2cc}) [13,20,21].

Although the impact of reconstruction uncertainties is limited under well-controlled circumstances it is nevertheless crucial to avoid accidental reconstruction errors which can lead to major dose deviations. Systematic errors in the applicator commissioning process can result in incorrect dose reporting for an entire patient population. For instance, an incorrect assessment of the ring cap thickness can lead to a systematic mispositioning of the ring channel in all patients. An error of 2 mm in the caudal direction can result in mean systematic errors of up to $10 \pm 2\%$ for target and OAR DVH parameters [11]. Similarly, a failure to correct for 4 mm slack of the source cable in the ring applicator would result in absolute mean DVH errors of $2 \pm 6\%$. Occasional errors due to manual mistakes (such as fusion errors) can also lead to substantial errors –

in particular for errors in anterior–posterior directions. Mispositioning of the vaginal sources by 3 mm in the anterior/posterior direction can increase the dose to the bladder/rectum by 20% in individual patients.

Conclusion

Geometrical reconstruction errors can lead to major dose deviations in target and OARs. Introduction of appropriate applicator commissioning and applicator reconstruction methods must be implemented in order to minimise reconstruction uncertainties and to avoid accidental errors as widely as possible. Clear and correct strategies for applicator reconstruction will ensure that reconstruction uncertainties have limited impact on delivered dose. Under well-controlled circumstances the reconstruction uncertainties are in general smaller than other brachytherapy uncertainties such as contouring and organ movement.

Conflicts of interest notification

We hereby state that there are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.radonc.2010.06.004.

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