Automatic Reconstruction of Catheters in CT Based Bracytherapy Treatment Planning

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Abstract -**The aim of this study was to develop an automatic reconstruction of brachytherapy catheters using CT data. Previously no such automatic facility has existed in any treatment planning software. To achieve this aim we have developed algorithms for the automatic reconstruction (which we term autoreconstruction) of plastic and metallic catheters. Our algorithms overcome a number of difficulties which arrise when a large number of catheters are present. These include situations with intersecting catheters and with loop techniques.**

Index Terms -**brachytherapy treatment planning, catheter reconstruction, computed tomography.**

I. Introduction

Modern brachytherapy treatment planning is image based[1-4] and frequently used imaging modality is CT scanning. CT based reconstruction accuracy depends on the CT imaging parameters such as the slice thickness, interslice distance and image resolution. In addition, accuracy also depends on observational ability of the user.

Image based treatment planning methods can significantly reduce the time required for the treatment planning process, to the use of projectional reconstruction methods using radiographs. Even so, a significant part of the treatment planning time is still spent in the reconstruction of catheters. From the analysis we made on 30 clinical implants the manual catheter reconstruction procedure took an average of 43.4% of the total treatment planning time: range of 22.6% to 71%. These times does not include those for image processing and contouring. The reconstruction time per catheter was an average of 151.2 s: range of 42.9 s to 312 s.

II. Material and methods

A. Introduction

The autoreconstruction process is based on post-implantation acquired CT images with the catheters *in situ* in their final positions. This includes the relevant patient anatomy, target volume(s), organs at risk, and the catheters. Catheter searching is made on a sequence of CT slices and is based on the Hounsfield number (HU) of the catheter material, catheter outer diameter, interslice distance, slice thickness and geometry of the catheter shape on the CT slices.

The slice thickness and interslice thickness must be adequately selected in order to take into account the curvatures of the catheters because these are not regular small diameter cylindres. We must therefore avoid loss of catheter area contrast in the reconstruction process during the CT slice acquisition. In general 3mm slice thickness and a 3mm interslice distance are satisfactory especiallly in cases when catheters *pass through* CT slices almost parallel to them, or when they lie on only a single CT slice and the neighboring region has very similar or significantly different (more than 2000HU) HU properties to that of catheters.

B. Definitions

The area on a CT image which represents a cross-section through the catheter volume within the slice is termed the *catheter area*. The terms *catheter poin/pixel* are used to describe any point/pixel which is automatically recognized by the algorithm or manually identified by user, and belongs to a given *catheter area*. From a catheter area one central point is considered to represent the *catheter describing point*[1] on the CT slice. Each catheter is considered to be a geometrical entity that can be described by a set of arbitrary points laying on the CT slices, the *catheter describing points*[1].

C. Hounsfield properties of the catheters

We analysed profiles of few different types of catheters[5-7] which derived the default HU ranges for the plastic catheters to be (-600÷-200) and for the metallic catheters (2800÷3071), see Appendix.

D. User defined parameters

Before the process of catheter autoreconstruction starts, the user must define some of the parameters that will be used in the search algorithm. These are: (a) catheter type: *plastic* or *metallic*, (b) serch region: *on-plane* (whole catheter lies in a single plane) or *in-volume*, (c) catheter tip position: *forward*, *backward* of the current slice (+ and – z direction in the DICOM definition[8]) and (d) catheter loop option.

E. Description of parameters

1.In-volume case

As input data, we have a single catheter point **P**(x,y,z), that the user defines through GUI on any CT slice for each catheter where catheter can be easily identified and does not intersect with another catheter. Firstly, the pixel region around that given point is searched until the last two connected pixels of the group are found with HU values within the selected catheter HU range. While there is any unsearched pixel in the tree-like process, this routine is repeated. Finally a list of all *catheter recognized pixels* on the CT-slice is built. The central point $\mathbf{P_C}$(x,y,z) of the *catheter recognized area* is given by the equations below.

$$P_C.x = \frac{1}{n} \times \sum_{i=1}^{n} C_i.x, \quad P_C.y = \frac{1}{n} \times \sum_{i=1}^{n} C_i.x, \quad P_C.z = Z_{CT}$$

n is the total number of *catheter recognized pixels* and C_i.x and C_i.y are their x and y coordinates. Z_{CT} is the z coordinate of the current CT slice where the recognition process was made. This central point is accepted as the first *catheter describing point.*

We now find the two most distant pixels in the *catheter recognized area*. They will be assigned as P_1 and P_2. From the Fig. 1 we can establish following relationship:

$$\cos(\varphi) = \frac{r_1}{r_2} \quad and \quad \varphi = \arccos\left(\frac{r_1}{r_2}\right)$$

where r_1 is the catheter outer diameter which depends on the type of catheter used, and r_2 is the distance between the centers of pixels P_1 and P_2.

From Fig. 1 we see that catheter can have two possible directions. Distance d is given by:

$$d = dist\,(P_C, P_{C1}) = dist\,(P_C, P_{C2}) = h \times \tan(\varphi)$$

where h is the distance between the two successive slices.

We now search for the next two *catheter describing points*, on the previous and on the next slice, based on the calculated distance d, the angle φ and direction of line l(P_C,P_{C1}), and l(P_C,P_{C2}) in the second case. We first find coordinates of two points P_{C1} and P_{C2}. The possible catheter centers on the previous and on the next slices will be points P_{C11} and P_{C22} in the first case, or P_{C21} and P_{C12} in the second case, Fig. 1. Points P_{C11} and P_{C12} have the same x and y coordinates as the point P_{C1}, and their coordinate z is the coordinate z of the next and previous slice respectively. It is analogous for points P_{C21} and P_{C12}. As we now have all possible catheter central points we need next to find which of these two point pairs (P_{C11},P_{C22}) and (P_{C12},P_{C21}) will determine the true catheter direction.

We first check if the HU number of the pixel to which point P_{11} belongs, lies in the selected HU range of catheter. If it does, then we set a distance d_{11} to 0mm, which means that this pixel belongs to catheter area. Otherwise, we search for the pixel P'_{11} with satisfying HU number in the four *rings* area around the pixel P_{11}. If there is no pixel found d_{11} is set to 100mm. Otherwise, d_{11} is set to the distance between the P_{C11} and P'_{C11}. In the same way we calculate distances d_{12}, d_{21} and d_{22}, that are distances from the points P_{C12}, P_{C21} and P_{C22} respectively to the nearest pixel that belong to catheter area. Then we calculate:

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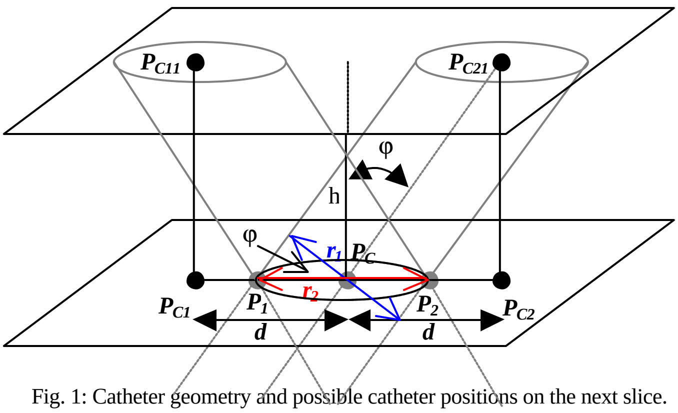


Fig. 1: Catheter geometry and possible catheter positions on the next slice. It is analogous for the previous slice.

$$d_1=d_{11}+d_{22} \text{ and } d_2=d_{21}+d_{12}.$$

If $d_1<d_2$, we accept the point pair (P'_{C11},P'_{C22}) as recognized catheter points, otherwise we accept (P'_{C12},P'_{C21}). For example, if the pair (P'_{C11},P'_{C22}) is accepted, and d_1=100mm, this means that we will search for the *catheter describing points* only in backward direction, as no catheter recognized point P'_{C11} was found on the next slice. If $d_{11}=d_{22}$=200mm the algorithm stop searching because no new catheter point can automatically be found. In that case, the algorithm requires manual intervention for the determination of the next searching direction.

The algorithm consists of searching backward and forward from the giving catheter point P in the –z and +z direction according to the DICOM definition[8]. The backward searching algorithm is given below.

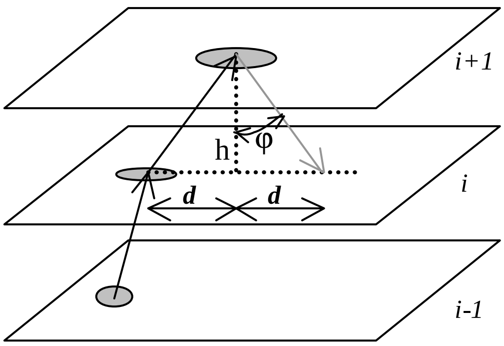


Fig. 2: Search of the next catheter point in the case when catheter makes a loop in-volume.

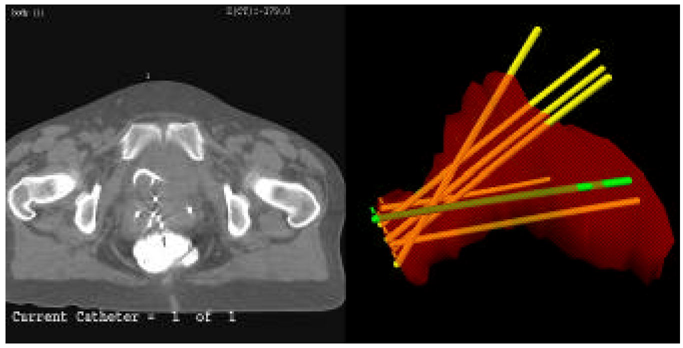
<u>Input data:</u>
P_C - center of the catheter recognized area;
P'_{C12}(P'_{C22}) – recognized catheter point on the previous slice;
Current_slice=P_C slice – 1;
<u>Processing</u>
put P_C in catheter describing point list;
error_flag=false;
Previous_point=P_C;
while(Current_slice s First_slice && error_flag==FALSE)
{Find catheter area A around the P'_{C12} (P'_{C21});
CP_C=central point of the catheter area A on a Current_slice;
put CP_C in catheter describing point list;
search_direction_line=extrapolated from points (Previous_point, CP_C);
New=the nearest catheter point to the intersection of the search_direction_line and the previous CT slice (Current_sliice-1). A search is made in a four rings around the proposed pixel.
If New is empty: error_flag=TRUE;
else{Previous_point=CP_C;
P'_{C12} (P'_{C21})=New;
Current_slice=Current_slice-1; }
}

After this the whole set of catheter describing points is available.

In the case of metallic catheters, artifacts can occur because of theirs significantly higher HU characteristic then this of other tissues. This is overcomed by checking the reconstructed catheter points, and *fix* the possible errors by *intential* over-jumping of the error-segment.

2.Loops in the volume

If catheter makes loops in the volume, we search it in the same way as previously described, except of the last step that need to be applied here. When the last point in the *forward* and *backward* direction is found, we analyse the shape of the catheter area on the CT slices of both the last found points in order to derive the next search direction from these, Fig. 2. After that we continue the process in exactly the same way.



(a) (b)

Fig. 3: (a) CT presentation and (b) 3D view of 8 plastic catheters in the case of cervix tumor.

3.On-plane case

If the entire catheter lies in a single plane, CT slice or calculated oblique cut, the search is made only in two dimensions[5-7].

F. Materials

Our algorithms have been tested in routine clinical practice. The implants were selected to include a representative spectrum of anatomical sites as well as implant geometry and different catheter types and materials. The sccuracy and time analysis have been done for 30 different clinical implants: prostate, breast, cervix, brain, chest, scapula, skin, neck and glioblastoma implants, and one phantom implant with three looped plastic catheters. Representative CT image and 3D view are shown in Fig. 3 for the case of cervix tumor.

A comparison of the accuracy and the time required was made for the classical manual catheter reconstruction from the CT slices, as implemented in Plato* BPS (Vs. 13.5) and for our autoreconstruction method.

III. Results and Discussion

The accuracy and time analysis have been done for implants described in *Materials*.

The *catheter describing point* difference analysis shows mean geometrical differences varying from (0.36±0.25)mm to (1.12±0.35)mm with a mean value over all 31 implants of (0.67±0.36)mm, whereas source dwell position based analysis (dwell positions produced at each 2.5mm starting from a given catheter tip) gave mean geometrical difference varying from (0.38±0.22)mm to (1.41±0.44)mm with a mean value of (0.87±0.36)mm.

The reconstruction time analysis presented next shows that our algorithm is extremely time-efficient. In 27 of 30 clinical cases (90%) no manual intervention by user was needed duting the autoreconstruction based process. With our algorithm reconstruction was 25.7 times faster than the manual reconstruction (21.4 s compared to 547.2 s for the manual procedure). For the cases where the manual intervention was needed, reconstruction based on our algorithm s 8.2 times faster than the manual one (81.7 s compared to 739.8 s for the manual procedure).

IV. Conclusion

Our autorecostruction algorithm significantly improves, simplifies and accelerates the imaging based brachytherapy treatment planning. The

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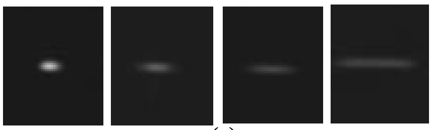
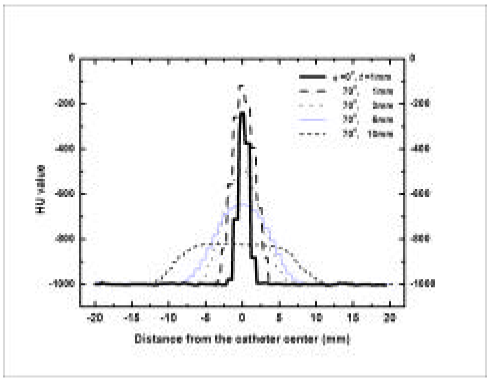
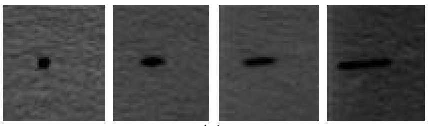


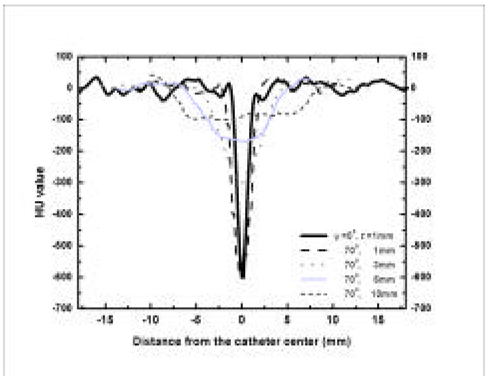
(a)



(b)



(c)



(d)

Fig. 4. Representative CT slices (a),(c) and HU profiles (b),(d), for a plastic flexible brain needle on the slices of 1 mm, 3 mm, 5 mm and 10 mm thicknesses in air and water, respectively. The angle φ is defined as the angle between the catheter axis and the orthogonal on the CT plane. For φ=70° the profiles are calculated along the ellipse's major axis of the *catheter area.*

time needed for catheter reconstruction decreases to only the time that the user spends defining the input parameters through the GUI. The entire process is fully controled by user, who can brachytherapy treatment planning procedure. Therefore accept or reject the reconstructed catheters. The success rate of our method in the cases tested was found to be as high as 90%. This improves the safety and reliability of the catheter reconstruction process. This innovative algorithm can revolutionize brachytherapy treatment planning in the 21st century.

V. Appendix

F. Hounsfield number properties of the catheters

The HU profile of the catheters on CT slice depends on the HU properties of the neighboring tissues or materials, on the slice thickness and on the angle at which the catheter enters the CT slice. This is because the CT images are smoothed during the reconstruction process of the CT slice acquisition.

We have analyzed the HU profiles of the flexible plastic catheters[5-7] which have an outer diameter of 2.0 mm, wall thickness of 0.25 mm and effective wall density of 1.019 g/cm^3. We have also analyzed profiles of brain implant flexible needles with an outer diameter of 2.0 mm, wall thickness of 0.3 mm and effective wall density of 1.42 g/cm^3. Finally, we analyzed profiles for stainless steel trocar point needles with an outer diameter of 1.9 mm, wall thickness of 0.2 mm and wall density 8.02 g/cm^3 . Some of our results for a plastic flexible brain needle are given in Fig. 4. All have been obtained using a Somatom Plus 4 CT scanner♦.

The HU profile observed for catheters depend on slice thickness, HU properties of the surrounding material and angle j between the catheter central axis at the catheter entrance position to the CT slice and the vertical axis through the CT slice. When the catheter is not orthogonal to the CT slice (j $\neq 0$) the *catheter area* on the CT slice has an ellipsoid shape and its HU profile along the ellipse's major axis is shown in Fig. 4 for j =70°. The default HU values we use are in the following ranges, [-600, -200] HU for typical plastic catheter material and [2800, 3071] HU for typical metallic catheter material.

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