Development of a Brain Phantom for Multimodal Image Registration in Radiotherapy Treatment Planning

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ABSTARCT

In radiotherapy treatment planning, it is critical to deliver the radiation dose to tumor and protect surrounding normal tissue. Recent developments in functional imaging and radiotherapy treatment technology have been raising chances to control tumor saving normal tissues. A brain phantom which could be used for image registration technique of CT-MR and CT-SPECT images using surface matching was developed. The brain phantom was specially designed to obtain imaging dataset of CT, MR, and SPECT. The phantom had an external frame with 4 N-shaped pipes filled with acryl rods, Pb rods for CT, MR, and SPECT imaging, respectively. 8 acrylic pipes were inserted into the empty space of the brain phantom to be imaged for geometric evaluation of the matching. For an optimization algorithm of image registration, we used Downhill simplex algorithm suggested as a fast surface matching algorithm. Accuracy of image fusion was assessed by the comparison between the center points of the section of N-shaped bars in the external frame and the inserted pipes of the phantom and minimized cost functions of the optimization algorithm. Technique with partially transparent, mixed images using color on gray was used for visual assessment of the image registration process The errors of image registration of CT-MR and CT-SPECT were within 2mm and 4mm, respectively. Since these errors were considered within a reasonable margin from the phantom study, the phantom is expected to be used for conventional image registration between multimodal image datasets..

Keywords : Brain phantom, Chamfer matching, CT, MRI, SPECT

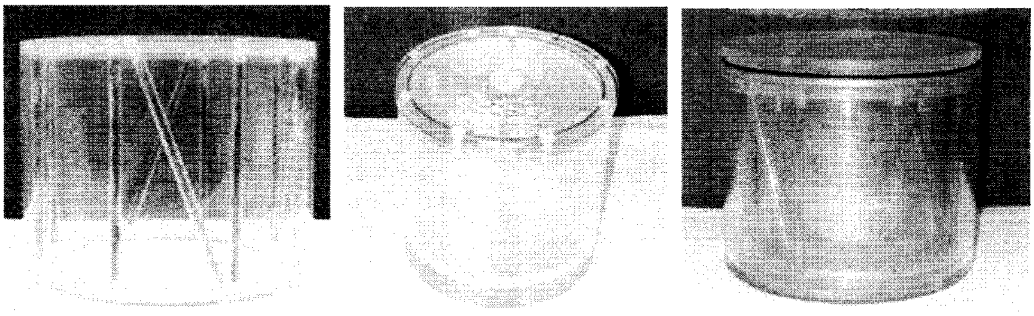
1. INTRODUCTION

There is a steadily growing demand from the clinic for multimodality imaging integration, in particular in neurosurgery and radiotherapy treatment planning and evaluation for more accurate delineation of target volume and better saving normal tissues[1]. Especially adopting a variety of physiological imaging tests including PET and SPECT imaging into radiation treatment planning has been developed and opening a new era to maximize the tumor control probability sparing surrounding normal tissues.

There are two kinds of image registration methods from the viewpoint of nature of matched properties : extrinsic and intrinsic[1,2]. Intrinsic methods are generally superior to extrinsic ones and their availability has been verified in many studies[3-5]. So we applied the intrinsic method - especially chamfer matching - for our image registration technique. Several methods are developed for the evaluation of the chamfer matching technique. However they were commonly carried out with cost functions for optimization procedures examining whether they were minimized(or maximized) or not. We studied a method to assess the accuracy of multimodal correlation visibly in addition to the current method. In our study, we made a brain phantom whose images can be acquired in CT, MRI, and SPECT with inserted fiducial markers which were not utilized for image registration but used for geometrical points comparison between registered images. The objectives of our study were (1) to develop a brain phantom that can be used for accuracy evaluation of image correlation visibly after image fusion; (2) to ascertain the reliability and accuracy of the chamfer matching method for clinical use; and (3) to develop a software of registration and evaluation tools which are suitable for the phantom.

2. METHODS AND MATERIALS

We designed the brain phantom with two main parts; one was an external frame with 4 N-shaped acrylic pipes which have 5mm-diameter holes for evaluation of image registration and relative z-axis coordinates deviations [Fig. 1(a)] and the other was an anthropomorphic brain surface without skull which was used for image correlation between different image data sets[Fig. 1(b)]. It was made by stacking 4mm acrylic plates where axial sections of human brain surface were carved. In the middle of the plates, there were two 2mm plates for inserting 8 acrylic pipes vertically to the section in the empty space of the inner part of the phantom which were filled with acrylic rods(for CT and MRI imaging) and Pb rods(for SPECT imaging). They were used for evaluation of image registration after correlation through comparison between the centers of the rods from multimodal images. The phantom was immersed in water when CT and MR images were acquired and for SPECT images ^{99m}Tc was added into the water. For registration method, chamfer matching was used. All the matching processing tool was programmed with 2 image processing programs; IDL(Research Systems, Inc., Boulder, CO) and Matlab(The Mathworks, Inc., Natick, MA).



a) b) c)

Fig. 1. The homemade brain

2.1 Image Data Acquisition

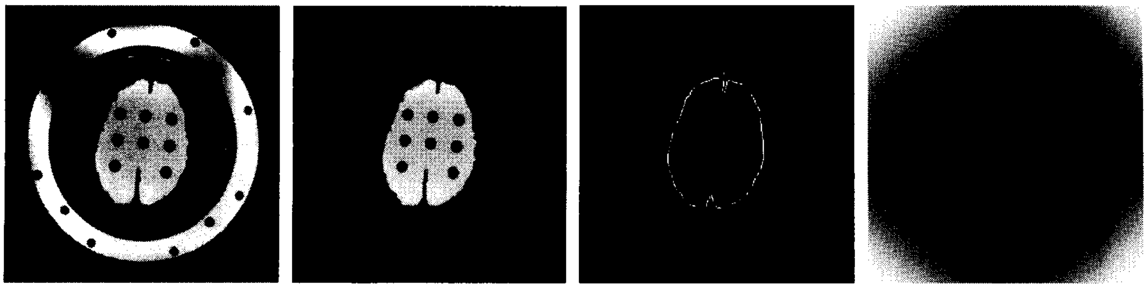
The phantom was imaged on a Somatom volume zoom(Simens Medical Engineering, Erlangen, Germany) CT scanner. The CT images were obtained with 2.5mm slice thickness. The matrix used was 512×512 with a field of view(FOV) of 278×278 mm, giving 0.54mm square pixels [Fig. 2(a)]. The MRI scan was performed on a Magnum 3T(Medinus, Seoul, South Korea) MRI machine. A volumetric MRI dataset was a axial, T1-weighted series consisting of 40 images of 3 mm slice thickness(TR/TE:600/12.6, FOV=256×256, 256×256 matrix, 1mm square pixels) [Fig. 3(a)]. The SPECT images were scanned with Simens E-CAM(Simens Medical Engineering, Erlangen, Germany). For SPECT scanning, 7mCi of ^{99m}Tc was applied into water. These scans contain 32 slices of 128×128 matrix image with 3.899mm slice thickness and 3.899mm square pixels.

2.2 Image Segmentation

The image of the external frame should be removed from the image slices because the chamfer matching is used. Only brain images were extracted from the image dataset[Fig. 2,3,4(b)]. A histogram was derived from all slices and one or two proper thresholds were applied to identify feature voxels in image dataset. Then edge detection was followed to extract brain contour from the image[Fig. 2,3,4(c)]. The feature points which would be used for matching transformation were extracted from CT contour image. The contour image itself can be used for the image registration. For MRI and SPECT images, distance transform is applied to the brain contour extracted by the edge detection to make chamfer map along 3 orthogonal axes [Fig. 3,4(d)].

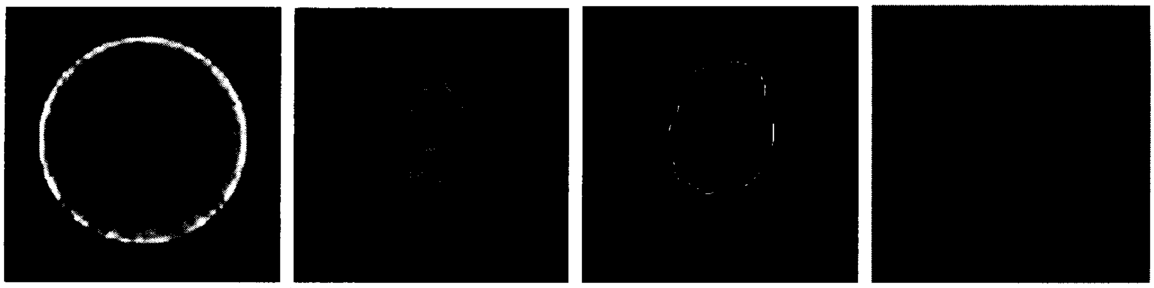
a) b) c)

Fig. 2. Contour extraction in CT



a) b) c) d)

Fig. 3. Distance transform with MRI scan



a) b) c) d)

Fig. 4. Distance transform with SPECT scan

2.3 Optimization Methods

To achieve the matching process within a reasonable time, optimization techniques must be used. The mean cost function in combination with the simplex optimization procedure has the best performance.

2.4 Image Registration

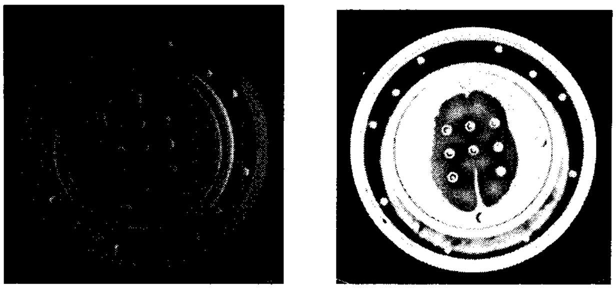
For 3 dimensional rigid body transformation between two different image studies, 9 degrees of freedom are taken into account : translation, rotation, and scaling along 3 orthogonal axes. But they can be reduced to 6 degrees of freedom with careful acquisition if image scaling is determined from the known pixel size and slice thickness of multimodal studies[10,11]. The reduced number of parameters are advantageous to the speed and the accuracy of a registration. One of the principal concerns during the optimization process is the risk of converging into local minima. To minimize this result, finding a proper starting point of correlation near to the final solution is a crucial factor for the best and fast registration. As proposed in other studies[10], the calculated initial point with the principal axes transformation(PAT) was used for reducing the iteration time.

2.5 Accuracy Evaluation

Evaluating the accuracy of the correlations among CT, MR, and SPECT scans were performed with comparison between centroid positions of the circle image for the fiducial markers inserted into the empty space of the phantom and the N-shaped configuration of the rods in the external frame from the different data sets. The external frame was introduced to access the accuracy of the 3D registration. From the comparisons of the relative marker positions on plane between original and correlated slice, we obtained 2D residual deviations along x and y Cartesian coordinate axes. To find z coordinate which corresponds to direction of axial scan, the N-shaped bars in the external frame were used.

3. RESULT

Fig. 6 shows results of CT/MR and CT/SPECT correlation for the phantom. To compare the accuracy of the registration, the MR slices were resliced into those corresponding to the CT study. The centroids of holes on the CT image dataset were compared with those of the MR study. The 7 or 8 slices out of total 49 slices were randomly selected for the evaluation. The rms deviation of corresponding markers and frame bars in the CT and MRI images has been found to be 1.98 ± 0.63mm which was slightly larger than the order of the sum of the pixel sizes between two studies. The accuracy evaluation of CT/SPECT corrleation was performed by the same way as the CT/MR case. The rms in-plane deviation was 1.42 ± 0.85mm. The order of this residual was smaller than the CT/MR registration because the total number of compared holes between CT and SPECT image were so limited due to the poor resolution of SPECT image. The marker holes of SPECT image were usually well visible in the center area. All the holes of the N-shaped bars in the external frame were technically not imaged so it was difficult to compare the 3D deviations of the registered images. The center points of the marker holes were determined by user intervention causing the deviation errors by several pixels. The results gave a value 3.69±1.07mm for rms deviation.



a) b)

Fig. 6. CT/MR correlation(left) and CT/SPECT correlation(right)

4. DISCUSSION

The study of multimodal image registration can offer researchers and clinicians a chance to define tumor targets more precisely.

To implement the chamfer matching study, two factors should be considered for the successful and fast correlation. These are (1) initial estimates of the transformation parameters (2) optimization technique and cost function. For our experience, the initial point of matching parameters is so critical to the method that it has to be decided as near as to the final solution for the successful matching. For optimization technique, Powell's method was a little more sensitive to the matching than simplex method so it has more chances to fail the matching.

Our matching and evaluation methods using the brain phantom is practical because it does not require the external landmarks or anatomical structure for the matching and the 3D accuracy of the matching can be calculated. For this matching method to be applied to clinical uses, however, several prerequisites must to be solved. The image structure of the real brain is more complicated than that of the phantom, therefore the more sophisticated segmentation technique has to be developed. Another problem of chamber matching is that there is no direct measurement of correlation accuracy. As the brain phantom was designed with the real brain image, if the segmentation of the brain image is performed properly, we are confident that the accuracy will be within the reasonable margin corresponding to the phantom study.

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