Deformable Image Tracking of The Parotid Gland for Adaptive Radiotherapy Application

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***Abstract*— Radiation therapy is a type of cancer treatment using radiation at different times defined as treatment sessions, distributed over different weeks. In each session, we have to determine and define the optimal treatment parameters for the patient. The aim of Adaptive Radiotherapy Treatment (ART) is to identify any change of initial parameters during the treatment course and modify the treatment plan for the purpose of maintaining optimal treatment objectives. In order to track the deformable image of biological organ such as the parotid gland, a 3D reconstruction is needed. 10 patients were scanned at the medical center of Oscar Lambret (Lille, France) using CT scan as imaging modality. The contours of the acquired images were extracted manually by the expert. Relaxed bi-cubic Bézier spline surface has been used in our study for the purpose of automatically reconstruction of the biological organ. Once the reconstruction is accomplished, the volume of the parotid gland at each session of treatment has been calculated for each patient. The obtained results show a decreasing of the volume of the parotid from one week to other one and a shifting of the detected center of gravity. These variations should be used to build a predictive model for adaptive robotized radiotherapy.**

***Index Terms*— Adaptive Robotized Radiotherapy, Deformable biological Organ, Relaxed bi-Cubic Bézier Spline Surface.**

I. INTRODUCTION

Adaptive Radiotherapy Treatment (ART) system is defined as the management of treatment feedback, planning, and adjustment the variations occurring during the radiotherapy [1]. Image Guided Adaptive Radiation Therapy (IGART) is a closed loop treatment process that is designed to include the individual treatment information, such as patient specific anatomic variation and delivered dose assessed during the therapy course in treatment evaluation and planning optimization [2]. ART is an off-line technique where the deformable biological organs parameters are determined during the treatment course. ART and necessitate advanced image processing techniques in order to follow and track the deformation of biological organ. The aim of image tracking is to follow and estimate the variation of the volume of the biological organ during treatment. Treatment using radiotherapy should follow a sequence of steps where the initiation of each step depends upon the successful completion of the former (Fig.1) [3]. Many factors determine the accuracy of the radiotherapy, such as the proposed technology during the treatment process that is meaning the imaging modality and treatment planning system.

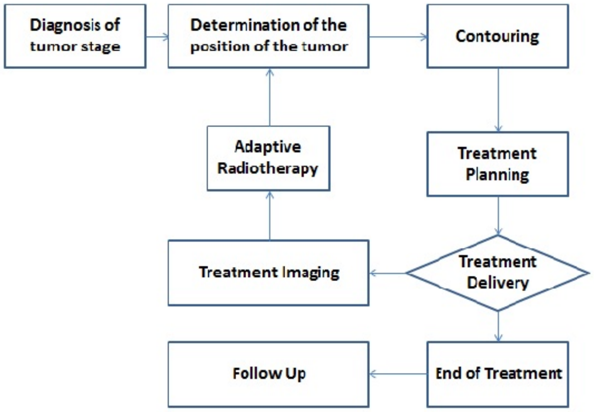

Fig. 1. Sequence of Adaptive Radiotherapy.

The principle of Adaptive Radiation Therapy appears when following the deformation of the biological organ during each session of treatment. For this reason, we have to adapt the treatment plan in order to match the deformation of the organ. Different imaging modalities can be used to record the position of the organ, such as CT scan, MRI, SPECT and PET. The aim of Adaptive radiotherapy is to reduce the dose received by healthy tissues and normal cells, and narrowing the dose only to the tumor. So, a re-planning of the original treatment is needed to accommodate the change in position of the biological organ during a robotized radiation session. Present studies accommodate target movement by expanding the beam to be sure that the treatment region remains within the irradiated field of view. This method increases the exposure of dose- limiting healthy tissue, imposing lower limits on the total treatment dose. There are different factors that contribute the geometric error and consequently the undesired delivery dose of radiation, such that inter- and intra- observer variations in Gross Tumor Volume (GTV) definition, motion artifacts due to respiration, motion during dose delivery due to respiration and heartbeat, variations caused by changing organ volumes, and tumor growth or shrinkage. Respiratory motion is the major contributor to the target movement and deformation in and around the thorax [4]. A tracking system must be used to limit the dose received by the patient and only by the cancer cells, and should be able

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to determine the position of the tumor, transmit the target coordinates to the realignment system through a control loop and finally reposition the beam [5]. Different methods have been used and developed to detect the tumor localization under treatment session. Controlled patient support system used to compensate the tumor motion in radiotherapy [6]. To accommodate the undesired movement and other errors, 4D active tracking and dynamic delivery has been used in the purpose of tumor motion prediction [4]. In [7], authors utilize automatic contour propagation algorithm based on surface construction by triangular mesh to evaluate parotid glands shrinking during radiotherapy. A dynamic multi leaf collimator (MLC) approach for adaptive radiotherapy is proposed in [8, 9]. Other methods have been used for the purpose of image and organ reconstruction or segmentation in order to follow the deformability of the biological organ during treatment. Different image processing techniques realize the proposed task. Authors in [10] propose an approach for automatic segmentation of liver complex geometries based on applying a graph-cut method initialized by an adaptive threshold. This proposed approach can be more satisfactory in the case of the tumors where are not close to the organ surface. Adaptive volume growing algorithm has been used to more accurately delineate a biological target organ in radiotherapy [11]. This technique has been tested on PET images with high noise characteristics and with law spatial resolution. In [12], the authors propose an automatic contour propagation method based on nonrigid B spline for lung cancer 4D adaptive radiation therapy. Using this technique, additional reductions in computational time are needed to fit in the clinical routine. Intends to improve radiation treatment by systematically monitoring treatment variations and incorporating them to re-optimize the treatment plan early during the course of treatment. In this process, field margin and treatment dose can be routinely customized to each individual patient to achieve a safe dose escalation [13]. During various treatment sessions, the processing machines are interacting with a deformable biological environment after each treatment. The efficiency depends highly on predicting successfully the deformable organ under treatment. As the aim of our study is to track the deformation of biological organ, a variation of the volume of the biological organ should be followed. Many patients should be processed at different sessions of treatment in the purpose of the evolution of volume variation. The other parts of the paper are organized as follows: the problem statement is discussed in section 2. In section 3 we propose a model based on relaxed bi-cubic Bézier spline surface for the organ reconstruction. Section 4 presents the application of the proposed method to the parotid gland in both sides left and right for 10 patients and the results obtained concerning the tracking of the desired volume. Conclusions are given in the last section.

II. PROBLEM STATEMENT

Radiation oncology (Radiotherapy) is a medical technique that concerns the radiation of localized tumor tissue during several sessions, under control of medical imaging systems. This technique describes a cooperation of technological system representing a robot, often manipulator with more than four degrees of freedom, and biological system, namely the tumor tissue. Such configuration is structured under the concept of system of systems [14]. Before starting treatment, the practitioner is based on an initial image (CT Scan or MRI) to identify the area to be irradiated and the dose required for all sessions. Except, with the evolution of treatment, the patient is going to undergo some side effects due to radiation, such as weakness, weight loss and microscopic deformation. These effects will influence the performance of the treatment technique. Despite the tools used for the macroscopic recalibration, this is insufficient for microscopic precision. So now it is possible to evolve the conventional technique to adaptive radiation. This adaptation depends on the accurate localization of the tumor target, which is often not easy to identify. Because, despite the existence databases of contoured irradiated zones, session by session, it is often not usable, due to the contouring is done differently by experts for each session. In this case, we do not have the same shape and contouring the same cup size image per session in order to properly reconstruct the deformation of organs and tumor tissues. Thus, we propose in what follows, a method of reconstruction of a deformable body due to radiation treatment, namely the parotid by interpolating several slices of images with different dimensions, performed at each session. The Fig.2 makes it easy to understand the challenge of adaptive radiotherapy. Above, we see the parotid contoured in red (first CT Scan, Fig.2-a) and yellow (Intermediary CT Scan, Fig.2-b). In down, the tumor in red is located in the center, while the parotid in the sides. It is noticed after superposition of the images (a) and (c), that in the final image (Fig.2-b), the parotid narrowed and migrated towards the center of the image and that the tumor has narrowed but remained in the same area at the beginning. Thus, if the patient receives the initial treatment plan, the parotid will receive more radiation than desired and the tumor tissues should be more targeted in order to limit the irradiation area. Several studies have been focused on the variation of the parotid glands. Thus, in [15] has shown that for 16 patients, it is possible to observe a volume reduction of about 5% from the original parotid, maximum narrowing of 4 mm between the two highest extremities, and in [16] the authors showed that the parotid volume decreased by an average of $0.19cm^3$ per day and moved an average of 3.1 mm during treatment and these changes become substantial from the fourth week of treatment. These studies show the importance of a tool for modeling the evolution of the parotid which must then be integrated with other tools to achieve the fusion of different information so that the robotized radiotherapy system becomes more accurate in guiding adaptively the beam in real-time.

An automatic deformable registration method is necessary to evaluate the narrowing of the biological organ during radiotherapy. A volumetric reconstruction or 3D reconstruction of the target is the most important step in assessing the

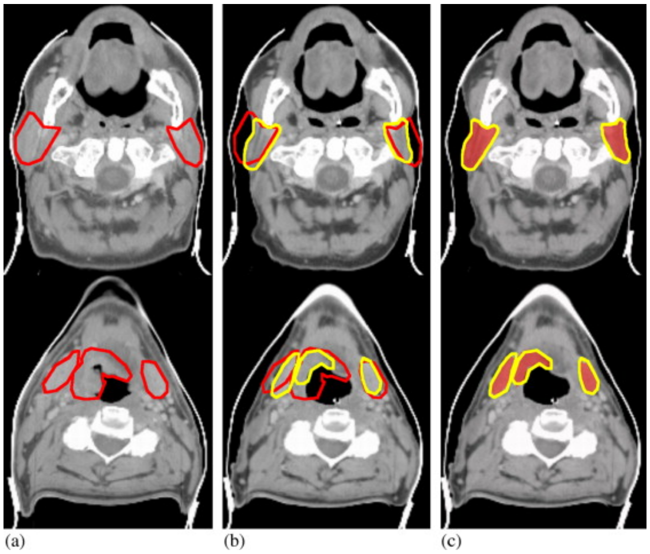


Fig. 2. Deformation of The Parotid Tumors.

biological tissue deformation with time before the application of artificial intelligence or statistical methods as predicting model. The aim of our paper is to propose a novel registration method that retains the important information of tumor shape and volume and take into consideration the advantages of the deformable registration. For this purpose a 3D reconstruction is desired in order to evaluate the deformable biological environment after each session of treatment. Once the reconstruction is performed, we identify the position of the center of gravity of the parotid gland for each session in order to achieve the time-evolution path of this center. The center will become the target to avoid irradiating within a safety region, covering the whole parotid for each treatment session. In each week of treatment the volume of safety region is also calculated.

III. MODELING OF TARGET EVOLUTION

In many different medical applications and especially the field of medical physics, biomedical engineering, medical sciences and computer aided design (CAD), the object or the biological organ is defined and presented by a sequence of 2D slices [17]. We can obtain these different slices by using the advanced technologies in medical imaging, such that magnetic resonance imaging (MRI), CT Scan, SPECT, PET and others. Each slice can be represented by a contour line. In this research, our aim is to track the movement of the tumor. For this reason, a 3D reconstruction of the target is needed. 3D reconstruction from these contours has become one of the major problems in all imaging techniques, and one of the main researches in Computer Graphics and Computer Aided Design (CAD) [18, 19].

Different algorithms for the purpose of image reconstruction have been used by many groups of researches, such as mesh based reconstruction method [18, 19, and 20]. Authors in [20, 21, and 22] use implicit function method and super-quadrics methods. B spline has been used by [23]. For the mesh reconstruction algorithm, there are many data points waiting to be processed on different contours, and for the reconstruction of more complex surface of object, these algorithms are not effective. For the B spline surface method, we can reconstruct smoothly the surface of the object, but in order to get knot vectors, they require the iteration method to solve the large scale system of equations. In this study, relaxed uniform bi- cubic Bézier spline surface has been used in order to reconstruct the object. Once the contour of an object is detected, it is resampled and reconstructed by interpolating the resampled points using bi cubic Bézier spline surface. In the following section, a detailed theory of the proposed method is cited.

A. B Spline Curve

To make a controlled-design curve with many control points is to use B-spline curves. The ones we shall discuss are called relaxed unifom cubic B-spline curves. We start by specifying a control polygon of points $B_0, B_1, ...B_n$,.We divide each leg of the control polygon in thirds by marking two "division" points. At each B_i except the first and last, we draw the line segment between the two nearest "division" points, and call the midpoint S_i. Then we have made an A-frame with B_i at the apex.

For completeness, let $S_0 = B_0$ and $S_n = B_n$. Finally, we sketch a cubic Bézier curve from each point S_i to the next, using as Bézier control points the four points S_i, two division points, and S_{i+1} as in Fig.3. As we see, the points of gluing meet the A-frame condition automatically and at the ends the second derivative is zero. Therefore we obtain a relaxed cubic spline curve.In our method, we need to find the Bézier control points in terms of the original B-spline control points: The "division" points on the line segment from B_{i-1} to B_i are $\frac{2}{3}B_{i-1} + \frac{1}{3}B_i$, and $\frac{1}{3}B_{i-1} + \frac{2}{3}B_i$. Also,$S_i$ is the average of the ends of its "cross-segment", so that:

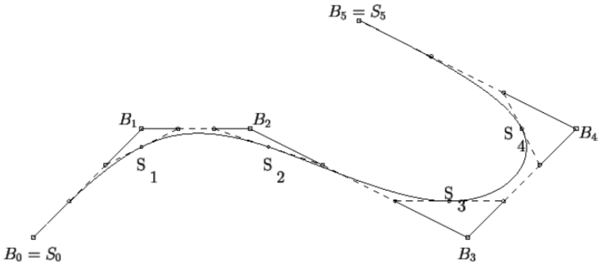


Fig. 3. A-frames for a relaxed cubic B-spline curves.

$$S_i = \frac{1}{2}(\frac{1}{3}B_{i-1} + \frac{2}{3}B_i) + \frac{1}{2}(\frac{2}{3}B_i + \frac{1}{3}B_{i+1})$$

$$= \frac{1}{6}B_{i-1} + \frac{2}{3}B_i + \frac{1}{6}B_{i+1} fori = 1, ..., n-1.$$

To summarize the computer method:

Given B-spline control points $B_0, ..., B_n$, we calculate $S_i = \frac{1}{6}B_{i-1} + \frac{2}{3}B_i + \frac{1}{6}B_{i+1}$ for i= 1,...,n-1. And let $S_o = B_0, S_n = B_n$. There are n Bézier curves to plot; curve i has

control points $S_{i-1}, \frac{2}{3}B_{i-1} + \frac{1}{3}B_i, \frac{1}{3}Bi - 1 + \frac{2}{3}Bi - 1$ and S_i. On curve i, we can plot points on the curve for, t= 0, 0.05, 0.10, , 0.95,1.
Finally, let's consider the situation mathematically. Let P(t) be the ith Bézier curve $(0 \leq t \leq 1)$. These n curves can be combined into a single curve P(t) for $0 \leq t \leq n$ by letting
P(t) =$p_1(t)$ for $0 \leq t \leq 1$,
P(t) = $p_2(t-1)$ for $0 \leq t \leq 2$, etc. In general,
P(t) =$P_i(t-(i-1))$ for $i-1 \leq t \leq i$, where $i = 1, ..., n$.
Then P(t) is a relaxed cubic spline curve. P(t) is called a uniform spline curve because its domain $0 \leq t \leq n$ was made from intervals all of length 1.

B. Bi Cubic Spline Curves

The bi-cubic Bézier spline surface is defined as a number of bi-cubic Bézier surfaces which are patched with G^2 continuity (in the case where the contour is a closed curve). In order to get G^2 continuity at each of the Bézier points, adjoining spline segments must have identical slopes and second derivatives at these points [17]. In 3D space, for initial control points B_{ij} (i=1,2,...m, j=1,2,...,n), we can use $m \times n$ bi-cubic Bézier surfaces to generate a bi-cubic Bézier spline surface which interpolates given control points.
The bi-cubic Bézier spline surface can be defined also as the combination of a series of cubic Bézier spline curve in horizontal direction called u direction, and a series of cubic Bézier spline curve in vertical direction called v direction. Since these spline curves are G^2 continuity in u, v direction, the bi-cubic Bézier spline surface is smoothly reconstructed for interpolating given points.

C. Reconstruction Algorithm Based on bi-Cubic Bézier Spline Surface

Our algorithm used for the purpose of 3D reconstruction is divided into different parts:

- **Contour optimization:** Computed Tomography Technique (CT scan) is used to obtain the desired images and after the desired contours. The contours corresponding to these images are extracted manually by the expert. As the contours of different slices are not efficient, there are too many redundant points. For this reason, and to eliminate the redundant points, a resampling of points should be done. Now, these resampled points constitute every contour. To resample data, angle matching technique is used. At first, we connect all neighboring points in one contour, two neighboring line segments compose an angle $\alpha i < \frac{\Pi}{2}$ at point B_i. We set a threshold α in advance.
  When $\alpha \geq \alpha_i, B_i, B_{i+1}$, and B_{i+2} can be supposed to be in the same line segment closely, so B_{i+1} can be removed.
- **Different contours corresponding points** interpolating using cubic Bézier spline curve: The resampled points of every contour are interpolated using relaxed cubic Bézier spline curve. The control point decision technique cited above is used to get the control points of cubic Bézier spline curve [22]. After interpolating the corresponding points in different contours using cubic Bézier spline curve, these curves can be understood as the isoparametric curves of bi-cubic Bèzier spline surface in vertical direction. At first, we should match all resampled points in different contours. The number of points in different contours may not be the same, so each point cannot be matched directly with other one. Suppose that the largest number of points for a given contour is M. In order to match each point with other one and to follow each point in the next contour, we have to increase the number of points to M for all other contours having the number of points less than M. Shortest distance rule and parameter based match method has been used for this purpose [17,24].
- **Reconstruction from contours based on bi-cubic Bézier spline surface:** The resampled points of each contour has been interpolated using the isoparametric curve of bi cubic Bézier spline curve in u direction, and all corresponding points in different contours can be interpolated using the isoparametric curve of bi cubic spline Bézier curve in v direction. So, all data (given points) has been interpolated by the bi cubic Bézier spline surface. Note that the patch point of the bi cubic Bézier spline curve in u, v direction should be in the same position[24].

IV. EXPERIMENTAL PROTOCOL AND OBTAINED RESULTS

CT (Computed Tomography) scan has been applied to ten patients suffered of cancer of parotid, at the medical center for the radiotherapy at Oscar Lambret at Lille France, in order to obtain the required images to be processed later. The obtained images correspond to the parotid in both sides left and right. A Computational Environment for Radiotherapy Research (CERR) software is used to import the images done by the expert for the proposed organ. Each week, the patient receives a given dose proposed by the expert. At each session, the expert draws the contours manually for the different slices taking into account that the volume of the organ decreases from one session to other one and the organ can migrate to the sagittal axis, the axis that separates the right side from the left side of the body. As the contour protocol is achieved manually, and in order to get the redundant points, a resampling of different points has been done. In order to reconstruct in 3D the desired organ, a bi cubic Bézier spline surface has been applied to each slice in u direction firstly. Fig.4 shows us the different contours after the application of the proposed method discussed above in u direction versus the different contours drawn manually. We can see that all contours are automatically smoothly reconstructed in horizontal direction. After we match the points in different contours, a bi cubic Bézier spline surface has been applied in vertical direction. Experimental results show us that the reconstruction of the object is smoothly using the bi cubic Bézier Spline surface. The center of gravity of each reconstructed object in each session has been

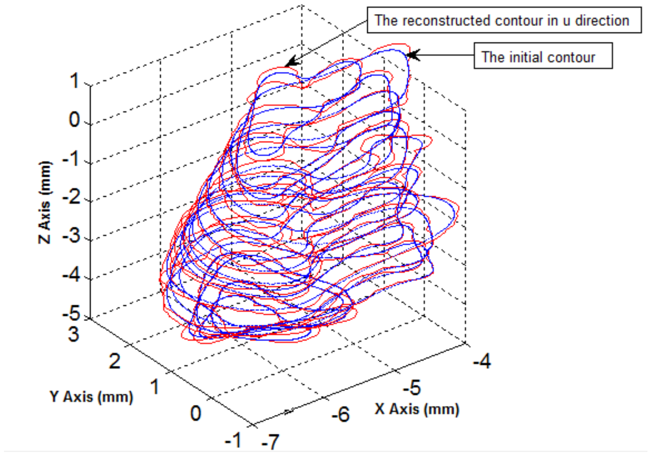


Fig. 4. Different contours obtained after the application of Bézier Spline Surface in u direction versus the initial contours

calculated using the following formula:

$$X_G = \frac{\sum(Position\ of\ x\ Coordinates)}{Number\ of\ x\ Coordinates}$$

$$Y_G = \frac{\sum(Position\ of\ y\ Coordinates)}{Number\ of\ y\ Coordinates}$$

$$Z_G = \frac{\sum(Position\ of\ z\ Coordinates)}{Number\ of\ z\ Coordinates}$$

In order to identify a safety region, that should be not irradiated, an external sphere around the reconstructed parotid has been sketched, centered at the detected center of gravity and with radius equal to the maximum distance from the center of gravity. As the tumor is close to the organ, and to be sure that the safety region is out of the normal tissues, the sphere has been sketched with a radius more than the real one by 10%. The Fig.5 shows us the safety region detected that covers the reconstructed parotid in 3D. The Maximum distance from the center of gravity has been calculated based on the above formula :

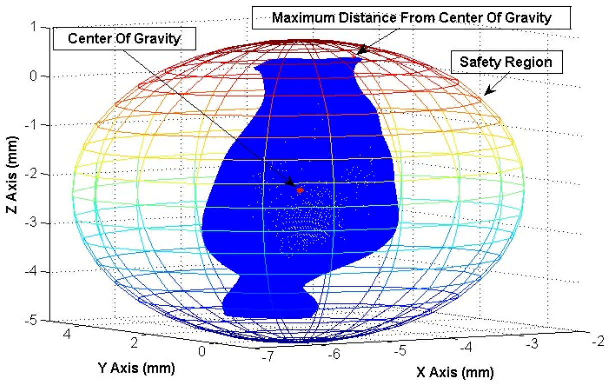


Fig. 5. Safety region covering the reconstructed parotid.

$$Distance = \sqrt{(X_G - X_i)^2 + (Y_G - Y_i)^2 + (Z_G - Z_i)^2}$$

where: X_G, Y_G and Z_G are the center of gravity coordinates, X_i, Y_i and Z_i are the coordinates of the different points on the reconstructed volume. To follow the time evolution path of the tumor, a safety region for the parotid should be found at each session. To do this purpose the center of gravity should be detected from one week to other.

A detailed study for all the patients has been realized to follow the evolution of the volume of the parotid, based on the calculation of the volume of the safety region (spherical region) that should not be irradiated. The obtained results show us a decreasing of the volume of the parotid and a shifting of the center of gravity in each session of treatment. TABLE I presents a statistical study for a given patient, shows us a decreasing of the detected maximum radius for each safety region and thus a decreasing in the volume of the parotid in both sides, left and right. The same table shows us a shifting at the center of gravity in each session.

TABLE I
STATISTICAL STUDY FOR A GIVEN PATIENT

	Left parotid				
	Center of Gravity			Maximum Radius	Volume Of Safety Region
	X	Y	Z		
W1	6.0671	0.6353	-2.7	3.5151	187.4363
W2	5.7125	0.4968	-2.25	3.4697	180.2767
W3	5.9078	0.2855	-2.15	3.2776	151.9639
W4	5.797	0.2259	-1.95	3.1372	133.2495
W5	5.9653	0.1761	-2.2	2.9751	113.6433
W6	5.9653	-0.0752	-1.95	2.7598	90.718
	Right parotid				
	Center of Gravity			Maximum Radius	Volume Of Safety Region
	X	Y	Z		
W1	-6.302	-0.041	-2.55	2.7727	91.9987
W2	-6.496	-0.212	-2.1	2.6299	78.5028
W3	-6.3601	-0.1048	-2	2.4468	63.2186
W4	-6.2724	-0.374	-1.8	2.4283	61.7933
W5	-6.142	-0.2963	-2.05	2.3643	57.034
W6	-6.0111	-0.3822	-1.8	2.278	51.0154

Fig.6 shows us a statistical decreasing of the volume of the parotid for all treatment patients.

Fig.7 shows us the variation of the reconstructed volume of the parotid from the first week of treatment to the last one. A decreasing of volume of 8.19% is detected. Note that some correction, in a defined number of patients, has been done for the estimation of the volume due to some human uncertainties.

V. CONCLUSION AND PERSPECTIVE WORK

In this paper, a new method is proposed to reconstruct the parotid in order to track the deformation of biological organ after each session of treatment. The method uses the bi cubic Bézier spline surface to reconstruct in 3D the target. The proposed method for reconstruction can be realized on different slices of the organ and the object is smoothly reconstructed. The center of gravity is calculated for each session

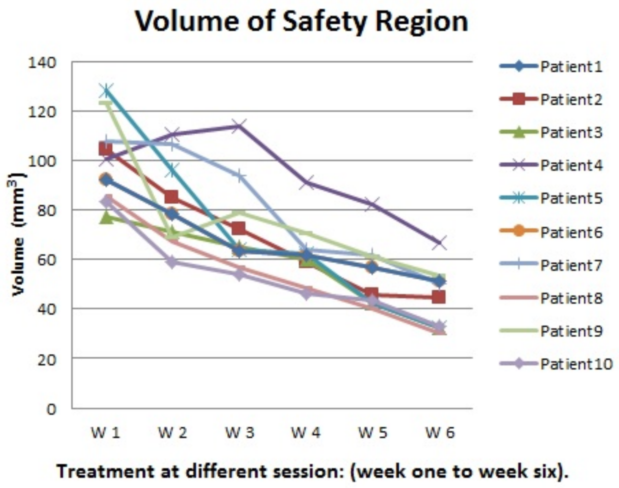
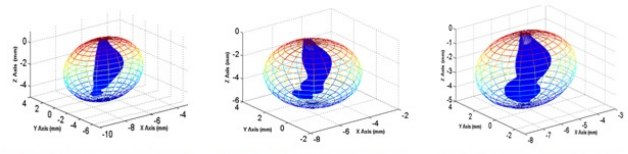
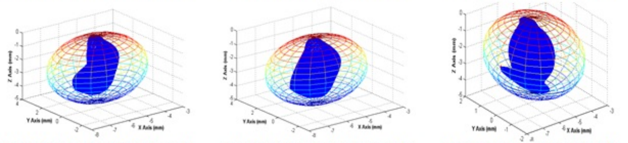


Fig. 6. Volume Variation Detected at Different Treatment Sessions For All Patients



Week1 (volume =187.4363mm³) Week2 (volume =180.2767mm³) Week3 (volume =151.9639mm³)



Week4 (volume =133.2495mm³) Week5 (volume =113.6433mm³) Week6 (volume =90.718mm³)

Fig. 7. Variation of The Reconstructed Volume Of The Parotid from the first week of treatment to the last one.

of treatment in order to identify the safe region of the parotid that should be not irradiated, based on the calculation of the maximum radius of the reconstructed volume. The proposed method is satisfactory for the tumor position measurements. The obtained results shows a decreasing of the volume of the parotid and a shifting of the center of gravity.The future work will be focused attention on a control strategy to compensate the change of tumor position. A control diagram consisting of a Model Predictive Controller (MPC) and a prediction algorithm such that statistical and artificial intelligence types, to predict future tumor position based on current tumor position measurements should be proposed.

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