A Double Scanning Procedure for Visualisation of Radiolucent Objects in Soft Tissues: Application to Oral Implant Surgery Planning

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Abstract. A procedure for visualization of radiolucent objects in CT scan images is proposed and applied to endosseous oral implant surgery planning. Many of these patients have a removable prosthesis, and visualisation of this prosthesis proves to be advantageous during planning. Such a prosthesis is usually quite radiolucent and thus not distinguishable on CT. The technique glues small markers on the prosthesis, and then scans it, giving a first image set. A second image set of the patient with the intraoral marked prosthesis is then acquired. From the first set, a surface rendered model of the prosthesis can be constructed. From the second set, a surface model of the bone can be made, and the markers indicate the position of the prosthesis in the mouth of the patient. The prosthesis model is then orthogonally transformed so that it fits the bone model. The views obtained are clinically very relevant since they indicate where the teeth of a later fixed prosthesis will come, and the planner can orient the axes of the implants towards the occlusal plane of the teeth. This double scanning procedure is a low-cost technique that nevertheless has significant clinical benefits.

Introduction

When patients with compromised bone quality are to receive oral implants, a preoperative plan is often made to assure optimal use of the remaining bone. This plan can be based upon computed tomography (CT), orthopantomography, or other scanning techniques (Jacobs and van Steenberghe (1998)). The available bone quality and -quantity are the most important parameter assessed as yet. However, the ability to evaluate the esthetics and biomechanics of a proposed implant configuration provides an added value. Many patients already have a removable prosthesis indicating optimal tooth position, which could be kept in the mouth during scanning to visualise it on the CT scans instead of a custom designed template. This is not evident however: Most prostheses, if they contain no metal, are not well visible when scanned intraorally. They have the same radiodensity as the soft tissues around them, making them undistinguishable from these tissues Even painted with a contrastmedium for CT, they suffer from streak artifacts due to the dental fillings in eventual remaining teeth. In standard jaw acquisitions where bone quality is to be judged these artifacts cause no problems because the scatter lies mainly in the occlusal plane, but for prosthesis design the position of the teeth in the occlusal plane is essential information that should not be lost.

A second acquisition of the prosthesis alone, scanned in the surrounding air, could be used to obtain its structure: The contrast with the surrounding medium is now sufficient, but a new problem is created: The position of the prosthesis relative to the patient's anatomy is lost.

To combine the best of both worlds, we use a *double scan technique*: Small radioopaque markers are attached to the prosthesis. A first scan of the marked prosthesis shows the prosthesis surface clearly enough together with these markers (Fig 1), and allows a good surface rendering of the removable prosthesis (Fig 2). Then a second scan of the patient and the intraoral marked prosthesis is made (Fig 3), showing the location of the markers with respect to the bone, but not the prosthesis itself. A surface model of the bone can be constructed however (Fig 4). The markers are visible in both sets and so allow the transformation between the two sets to be computed. Once this transformation is known, the scan of the prosthesis can be realigned with the scan of the patient, and both can be inspected together. When following this procedure, several things must be kept in mind however. We will now go into more detail.

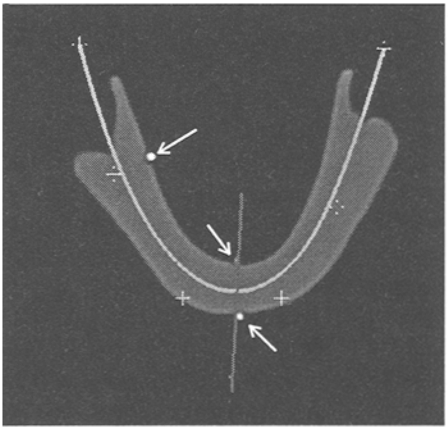

Fig. 1. Prosthesis scanned separately. The arrows point at the attached markers.

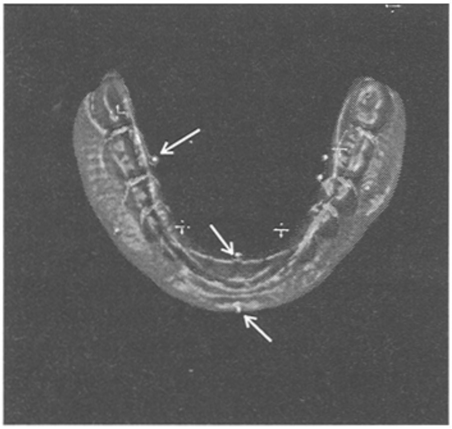

Fig. 2. The model made from the previous images, showing the markers from (Fig 1) as small balls on the structure.

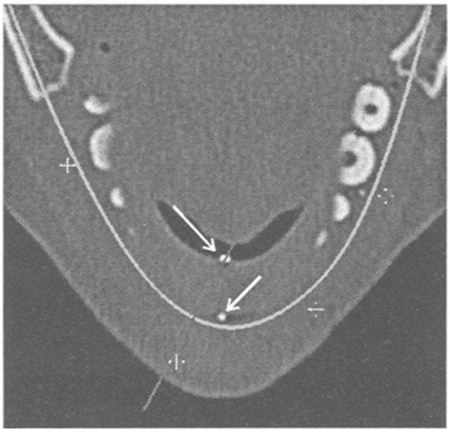

Fig. 3. The markers from (Fig 1) are visible on the patient scan images.

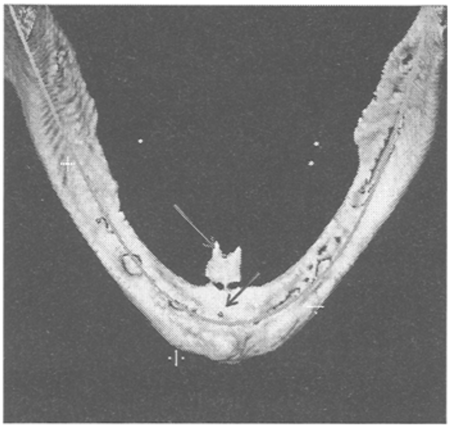

Fig. 4. The markers are manually indicated by small annotation spheres.

Methodology

Equipment

For the acquisition, a Somatom Plus CT (Siemens, Erlangen, Germany) is used, in spiral mode with a table feed of 1 mm/rotation together with an aperture of 1 mm. Reconstruction is at the theoretically optimal interslice distance of 0.5 mm. A maximum height of 40 mm can be scanned with this CT and these settings, but this is sufficient for these structures.

The reconstructed data are transferred to the workstation over the intranet of the hospital. The fiducials are Gutta-Percha balls and are attached to the prosthesis with simple pieces of adhesive tape. They are disposable.

Scanning Procedure

Prosthesis CT

Meticulous execution of the steps in the sequence avoids some pitfalls. The prosthesis should indicate optimal teeth location and -angulation, and it should not contain large metal parts because they will create streak artifacts that obscure the fiducials and even the bone of the jaw. A uniform distribution of the markers over the available height and width is ideal, but if the patient is not edentulous he might have fillings, and in that case it is best to avoid placing markers within the occlusal plane. The available space for the markers is then much less in height and care must be taken to attach enough markers to avoid coplanarity. The prosthesis is fixed to the scanner table with approximately the same angulation as it will have in the mouth of the patient, to avoid distortions comparable to those introduced by gantry tilt. If all requirements are fullfilled, the prosthesis is scanned. Streak artifacts in the images will warn the technician if any invisible larger metal parts were overlooked. If this is the case, the procedure cannot be used and the patient is scanned without the prosthesis, as for the normal dental CT. If there are no such problems however, the patient is scanned with the prosthesis intraorally.

Patient CT

The marked prosthesis is placed into the mouth of the patient as it is usually worn. The head of the patient is aligned with the palate for the maxilla and with the lower mandibular border for the mandible. If there are dental fillings present, this orientation will keep the streak artifacts out of the plane of the jawbones. Once proper alignment is reached, the head is immobilized relative to the scanner table. Patient and prosthesis are scanned together using the normal settings for this type of acquisition.

Data Handling

Both data sets are reconstructed on the CT console and the images are transferred to the workstation by any suitable means. Several preprocessing steps prepare the data (Schroeder and Lorensen (1996)), amongst them the creation of the surface renderings for bone and prosthesis, using the marching cubes algorithm (Lorensen and Cline (1987) or Udupa and Gon÷alves (1996)).

Fiducial Indication

The images are inspected on the workstation. In each of the datasets the coordinates of the visible fiducials are indicated by putting a spherical marker on them. These coordinates could just as well be determined on the scanner console, but care should be taken that a reslice along the z-axis is taken for this selection, since otherwise a rounding on the slice position will occur, resulting in coordinates that are a multiple of the interslice distance.

Two sets result, called X_1 and X_2, for the patient and the prosthesis scans respectively. The center of the marker is indicated manually on the reslices along the z-axis, but the images should be zoomed out sufficiently to increase the accuracy. Visual comparison of both marker sets provides a first check on the correctness of the indications. Sometimes scatter artifacts make marker selection difficult in the patient data set, but the prosthesis data serve as a map that gives a hint as to where the user should look for the markers in the patient set.

Registration Procedure

Statement as a multidimensional Least Squares Problem

Adjusting the position and orientation of the prosthesis relative to the bone of the patient is called registration. This registration problem can be stated as follows:

Given two sets of coordinates X_1 and X_2 for the same points in two different reference frames, that of the patient and that of the prosthesis, a matrix T is sought that transforms one set into the other, where $X_1, X_2 \in \Re^{4\times m}$ and $T \in \Re^{4\times 4}$:

$$X_1 = TX_2 \tag{1}$$

Solving (1) for the transformation matrix T is similar to the following mathematical problem:

Given a data matrix $A \in \Re^{m\times n}$ and an observation matrix $B \in \Re^{m\times d}$, find a matrix $X \in \Re^{n\times d}$ such that $AX = B$. If $m > n$ there are more equations than unknowns and the problem is overdetermined. In almost all cases there are errors on the data so that $B \notin R(A)$ and there is no exact solution. The notation then used is $AX \approx B$. Solution methods can be found by considering the problem as a multidimensional Least Squares (LS) problem:

Definition: Multidimensional Least Squares Problem:

$$\text{Find the } X \in \Re^{n\times d} \text{ that minimizes } \|AX - B\|_{Frob} \tag{2}$$

X is then called a LS solution of the set $AX \approx B$. This solution is in a sense ideal since it has been shown in (Gauss (1823)) that the X that can thus be found has the smallest variance that can be produced if there is no systematic error in the result and X depends linearly on B.

Solutions for the LS Problem

For a solution of (2) to exist, B has to be a part of the range of A. If the problem is overdetermined this is not likely to be the case. The equations are first converted to the so-called normal equations:

$$A^T AX = A^T B \text{ with their solution } X = \left(A^T A\right)^{-1} A^T B \tag{3}$$

This is not a solution that is numerically ideal. A better solution is given by the Singular Value Decomposition (SVD), a powerful computational tool for solving LS problems (Golub and Van Loan (1989)). This decomposition is defined as:

Definition: Singular Value Decomposition:
Every matrix $A \in \Re^{mxn}$ can be factorized as

$$A = U \Sigma V^T \tag{4}$$

Where $U \in \Re^{mxm}$ and $V \in \Re^{nxn}$ are orthonormal matrices and Σ is a real $m \times n$ matrix containing $\Sigma_r = diag(\sigma_i)$. The $\sigma_i \in \Re_0^+$, with $\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_r \geq 0 \ \ \forall i$ are called the singular values of A. The corresponding columns of U and V are called the left and right singular vectors.

Application of this SVD factorization for A yields another solution that is numerically more stable:

$$A = U \Sigma V^T = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{pmatrix} S & 0 \\ 0 & 0 \end{pmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix} = U_1 S V_1^T \tag{5}$$

with $S \in \Re^{rxr}$, $r = rank(A)$ and U and V partitioned accordingly. Insertion into the normal equation (3) results in the expression

$$\left(V_1 S^T S V_1^T\right) X = V_1 S U_1^T B \tag{6}$$

so that a general solution can be written as

$$X = V_1 S^{-1} U_1^T B \tag{7}$$

Decoupling of the Parts of the Transformation Matrix

The solution methods seen will yield a solution for the transformation matrix but the rotational part of this matrix will not necessarily be orthogonal, meaning that the transformation might induce deformations into the prosthesis model. This is an undesirable effect and can be avoided by separately determining the translation and rotation, and solving for the rotational part by an extension of the LS method. Differences in scaling will normally not occur since the CT scanner will mention the zoom factor used in the images, so that an eventual different zoom factor can be corrected in a preprocessing step.

The first step will be to determine the centers of inertia for both coordinate sets and to translate each set so that its center of inertia coincides with the origin:
For the m markers of each set:

$$\text{If } A = \left[a_1, \ldots, a_n\right]: \ \mu_A = \frac{1}{n}\sum_{i=1}^{n} a_i \text{ and } \forall a_i \in A\text{: } a_i = a_i - \mu_A \tag{8}$$

Once both sets are centered around the origin, the orthogonal rotation matrix that rotates one set into the other has to be found. This is called an Orthogonal Procrustes problem (Golub and Van Loan (1989)), and is a special case of the LS problem above, with an additional constraint:

Definition: Orthogonal Procrustes Problem
Given a data matrix $A \in \Re^{m\times n}$ and an observation matrix $B \in \Re^{m\times d}$, find a matrix $X \in \Re^{n\times d}$ that

$$\text{minimizes } \|B - AX\|_F \text{ subject to } X^T X = I_d \tag{9}$$

The solution to this problem can be derived by noting that if X is orthogonal, then

$$\|B - AX\|_F^2 = trace(B^T B) + trace(A^T A) - 2trace(X^T A^T B), \tag{10}$$

so that minimizing (10) is equivalent to maximizing $trace(X^T A^T B)$. The X that maximizes this expression can be found through the SVD factorization of $A^T B$:

$$U^T\left(A^T B\right)V = \Sigma = diag(\sigma_1,\dots,\sigma_p) \tag{11}$$

Define $Z = V^T X^T U$ so that

$$trace(X^T A^T B) = trace(X^T U\Sigma V^T) = trace(Z\Sigma) = \sum_{i=1}^{d} z_{ci}\sigma_i \le \sum_{i=1}^{d} \sigma_i \tag{12}$$

The upper bound of this expression is attained by setting $X = UV^T$, for then $Z = I_d$. So the orthogonal rotation that turns one set into the other will be given by

$$X = UV^T \tag{13}$$

Error Analysis

Error Sources

The whole procedure involves several steps, ranging from acquisition to registration, and each of these may introduce some errors in the data:

- *Acquisition errors*:
1. Distortions in CT images.
2. Patient movement artifacts.
3. Loosening of the fiducials.
- *Registration errors*
1. Badly conditioned problem, due to coplanarity of markers.
2. Distorting transformation matrix.
3. Numerical errors.
- *Errors in fiducial coordinate determination*
1. Markers are indicated off-center (Not zoomed in during indication).
2. Indication of markers on axial plane with corresponding rounding to a multiple of the interslice distance.

3. Erroneous correspondency between fiducial sets (wrong order).
4. Wrong coordinates for one or more fiducials, often due to streak artifacts obscuring the markers.

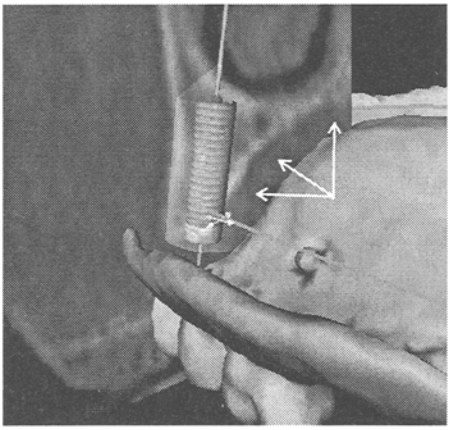

Fig. 5. A small error in the registration would show in the gap between the palate and the prosthesis (arrows).

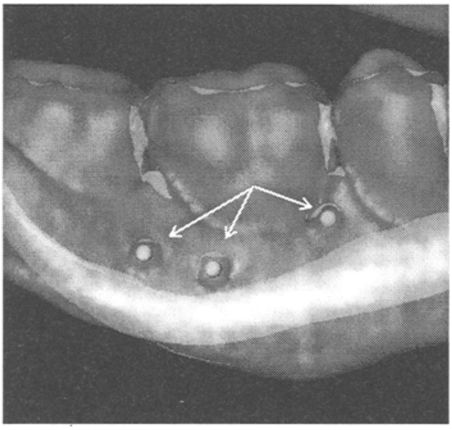

Fig. 6. After transformation, the prosthesis fiducials nicely surround the points that represent the patient fiducials (arrows).

Checks on the accuracy

It is very important to ensure that no insidious errors are overlooked. Several precautions can be taken to warn about some of the error sources mentioned above:

1. Visual check of surface models: Prosthesis must fit to the bone and to the soft tissue visible on the grey value slices. Prosthesis fiducials must surround points indicated on patient scan.
2. Visual check of point sets on fiducials: Overlay of point sets is more sensitive to errors.
3. Distances between consecutive points within the same set should be the same when compared between both sets.
4. The determinant of the resulting rotation matrix should be 1 and not –1 (equivalent to mirroring the model).
5. The condition number of a matrix can be defined in terms of its SVD and is then given as $\kappa(A) = \sigma_1 / \sigma_n$. A large $\kappa(A)$ means that a small error on the measurements will be amplified in the solution of the LS problem. This is an indicator that more points must be collected to improve the condition.

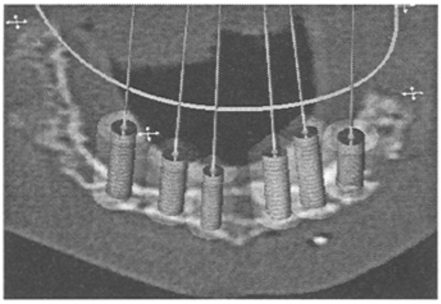

Fig. 7. Combination of 2D grey value slices, CAD models of implants and the curve guiding the reslices.

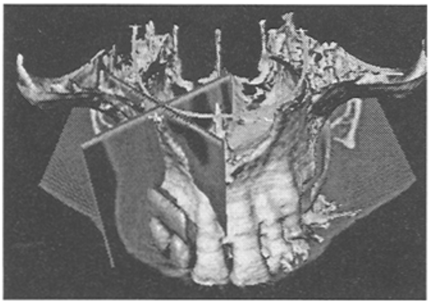

Fig. 8. 2D and 3D information together, adding soft tissue information to the surface models.

Results and Discussion

The Planning System

In our center we use a generic library suitable for planning many different types of surgery, that is specifically instantiated and extended for implant surgery (Verstreken et al. (1996)). This package allows all standard visualization methods available on the scanner console, and adds multiplanar reslicing, eventually along a curviform path. 3D CAD models of implants can be added to the scenery and manipulated within it (Fig 7). Two-dimensional (2D) grey value information and the implant models are shown together with three-dimensional (3D) surface rendered models (Fig 8).

Benefits of the Prosthesis Model for the Planning

The advantages are manyfold. The superstructure is now included in the planning stage, and the surgeon can adjust his plan to facilitate the work of the prosthodontist, where the bone allows it. A number of problems may otherwise occur, making a prosthesis difficult to design or more expensive to make. Axes may come out of the gums at the labial side of the teeth (Fig 9-10), which may be very difficult to hide. For the same reason, interdental implant axes are to be avoided, especially in the frontal area.

Other construction problems can be caused by axes that are too palatal, since they come in a prosthesis part that is too thin to provide support for the abutment (Fig 11-14). It is nearly impossible to predict such complications from the normal 2D planning, or even from the 3D bone surface model.

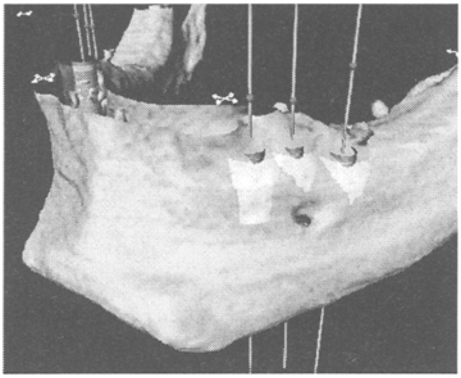

Fig. 9. This seems a good configuration for bone and implants.

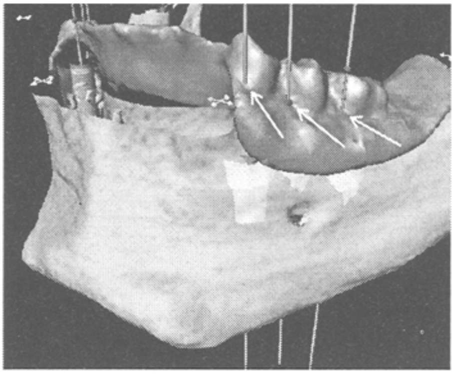

Fig. 10. But her it is seen that the axes are at the outside of the teeth (arrows).

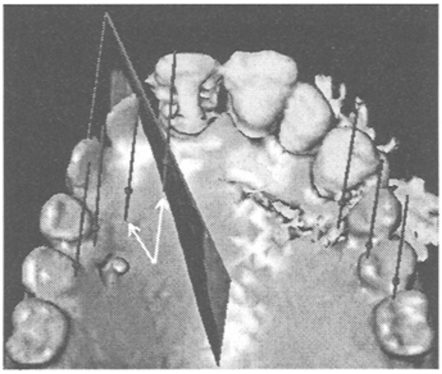

Fig. 11. These axes (arrows) are too palatal. The prosthesis is too thin in this area.

Fig. 12. The 2D slice shows how the prosthesis extends in front of the bone.

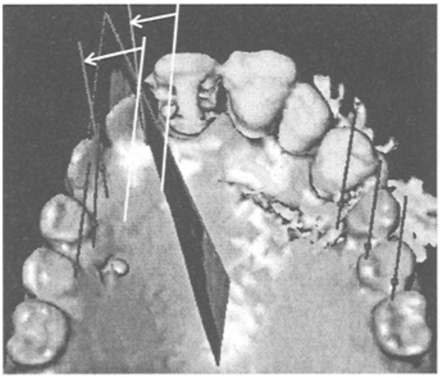

Fig. 13. The axes from (Fig 13) are shown by the lines. Adjustments to the orientation were made on this view.

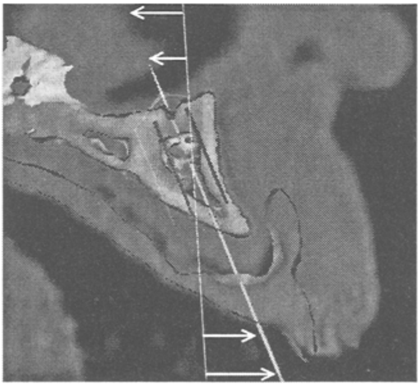

Fig. 14. Further corrections were needed here to keep the implant within the bone.

In many larger centers there is a preoperative consultation where both the prosthodontist and the oral surgeon are present. The images from the bone with the matched prosthesis include elements from both subfields and may be an ideal discussion and demonstration tool. A deliberation considering the relative importance of all design factors: Bone, biomechanics and superstructure is now greatly facilitated.

Conclusion

The double scanning procedure that is proposed is a technique that yields impressive benefits at a very low cost. There is no additional radiation dosage for the patient and no expensive radioopaque temporary prosthesis has to be made. Streak artifacts pose no problems and inaccuracies are immediately visible. The algorithm for the registration is straightforward while the planning advantages are clear. In our opinion this is a technique worth incorporating into routine dental scanning procedures, whereever 3D visualization technology is available.

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