The Accuracy of Cone Beam Computed Tomography-based Registration and Multislice Computed Tomography-based Registration for Oral and Maxillofacial Surgery: A Systematic Review

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Abstract

Objectives: Advances in medical imaging technologies have paved the way for facilitating great challenges in the field of oral and maxillofacial surgery. Medical image registration has become an essential step for a variety of procedures. The goal of this review is to systematically try to answer the following question: Is CBCT based registration and MSCT based registration reliable for maxillofacial surgery? Methods: The PubMed databases, the Lilacs databases and the Chochrane library for systematic reviews were searched till 1 June 2016. Results: The search yielded ten articles evaluating MSCT and CBCT registration techniques after application of certain exclusion criteria. Conclusion: Only one study was comparing the accuracy of CBCT and MSCT registration (markers) for image guided surgery, two studies evaluating CBCT landmark registration technique, four studies evaluating CBCT voxel based registration technique one study comparing the accuracy of CBCT surface based registration and voxel based registration and one study comprised two parts: evaluation of CBCT landmark registration and CBCT voxel based registration.

Keywords: Cone Beam Computed Tomography, Maxillofacial Surgery- Review, Multislice Computed Tomography, Registration- Image Fusion- Oral

1. Introduction

1.1 Statement of the Problem

Medical images acquired using different imaging modalities like Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Positron Emission Tomography (PET), Ultrasound (US), etc., are used for diagnosis, treatment planning, disease monitoring and image guided surgery.1

A fundamental problem in medical image analysis is the integration of information from multiple images of the same object or from different objects, acquired using the same or different imaging modalities and possibly at different time points.2 3

The information integration process involves two steps: image registration and image fusion.4 Image registration is the determination of a geometrical transformation that aligns points in one view of an object with corresponding points in another view of that object or another object.5

Registration is merely the determination of that relationship. If the corresponding points are mapped together, the registration is successful.6 Image fusion is the process of presenting the data in a common display.7 So that Image registration is a crucial step for image analysis procedures and can be considered as a core technology for many imaging tasks.8

Registration of Computed Tomography (CT) images to Magnetic Resonance Imaging (MRI) and Positron
Emission Tomography (PET) images followed by images fusion has become an important step in radiation therapy especially with the development of more sophisticated radiation therapy techniques such as Intensity Modulated Radiation Therapy (IMRT).

Computed Tomography (CT) is the gold standard for radiotherapy planning, since it is the only imaging modality able to provide information in terms of electronic density for dose calculation. The importance of additional information from Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET) images is for precise delineation of tumor tissue and reducing uncertainties in image interpretation.

Assessment of craniofacial growth and growth interactions between dental and skeletal components is a main step in orthodontic treatment. This step is done using either 2D or 3D imaging modalities. This is done by follow-up of craniofacial growth and development of the patients by registering serial 2D or 3D images to a reference image using stable structures, providing comprehensive visual and quantitative analysis.

Monitoring of disease progress and treatment changes can be done by registering images acquired from subjects at different time points and the pre- and post-intervention images.

The interpretation of these registered images allows the operator to understand how changes in size, shape and shifts in relative positions of skeletal and soft tissue facial components contribute to orthodontic, orthopedic, orthognathic surgery treatment changes and short and long-term stability.

Examples for the use of registration in assessment of disease progress and treatment changes include the work done by Cevidanes and colleagues who studied the effect of maxillary orthognathic surgery on mandibular anatomy by registering before and after CBCT scans. Also the work done by Chen et al 2009 for quantification of tooth displacement from CBCT images which is considered an important outcome of orthodontic treatment to evaluate treatment strategies and orthodontic appliances.

A commonly used method for quantitative changes measurements is the use of color maps which was proposed by Geric et al 2001. This tool calculates thousands of surface distances in millimeters between 3D models surface triangles at two different time points. The color maps indicate inward (blue) or outward (red) displacement between overlaid structures. An absence of changes is indicated by the green color. Treatment outcome changes are described not as absolute displacement but as displacements relative to the cranial base.

One of the main concerns of orthognathic surgeons needed for the 3D planning to properly position the jaws and to reach a stable occlusion, is accurate representation of the anatomical occlusal details as well as the occlusion.

Computed tomography and cone beam computed tomography scans cannot provide accurate dental surfaces and intercuspation level due to many reasons; for example: the density of enamel is high, that gives rise to artifacts around the teeth, brackets (always worn by orthognathic patients) cause scattering at the occlusal level, teeth are related in occlusion and touch each other, which turns segmentation of maxillary and mandibular teeth extremely difficult and the required accuracy for teeth segmentation is higher than the bone segmentation accuracy, which would necessitate a scan with higher resolution.

Digital models are similar to plaster models when used during diagnosis and treatment planning. Integration of digital models into the patient’s skull model offers the possibility of precise diagnosis, 3D planning and also to assess changes caused by treatment, growth, or relapse.

Several methods have been proposed to integrate digital dental casts in CBCT scans. A group of researchers proposed a method, based on a best fit matching of scanned plaster models with the dentition in the CBCT scans, after removal of streak artifacts due to brackets or amalgam restorations. Other researchers proposed a method using bite jigs, with fiducial markers attached to it.

The patient wears the bite jig when the CBCT scan is made and afterwards the bite jig is scanned together with the impressions. After data processing, the fiducial markers are visualized on both the CBCT scan and the scan of the bite jig with the impressions. Both data sets are then matched, using the fiducial markers as reference points.

In the article developed a triple scan method, using an impression tray in which both the upper and lower jaw are registered. For this procedure, a high resolution CBCT scan is made of the patient in rest. Next, a low resolution CBCT scan of the patient is made, with the impression tray placed in the mouth. Finally the impression scan is scanned separately. With dedicated software, the impression scan is placed into the CBCT scan of the patient, using the impression tray in the low resolution scan as reference.
Another method has been introduced by the article which is the integration of digital dental casts into CBCT scans, using fiducial markers glued to the gingiva. These images are the foundation of rapid prototyping, and computer-aided design and computer-aided manufacturing applications.

Another use of digital models registration by the article is the registration of digital models to 3D photos. For the integration, 3 Digital data sets were constructed: a digital dental cast, a digital 3D photograph of the patient with the teeth visible, and a digital 3D photograph of the patient with the teeth in occlusion. By using a special registration technique, these 3 data sets were matched to place them in the correct anatomical position.

Three dimensional analysis of soft tissue is an important step for orthognathic surgery and orthodontic treatment. In the planning phase, it allows assessment of facial deformity by locating the source of deformity and its magnitude as well as soft tissue establishes the limit to which the operator can alter the position and the dimensions of the dental arches considering the esthetic outcome and treatment stability.

In the postoperative phase, three-dimensional analysis of soft tissue allows assessment of treatment outcomes for example: soft to hard tissue displacement ratios, facial soft-tissue changes following functional treatment, following extraction and non-extraction orthodontic treatment, and in cleft lip and palate patients.

Computed tomography scanning has limited resolution of facial soft tissue surface details due to slice spacing and cannot record the optical properties of soft-tissue surfaces, so the solution is to capture the soft tissue image using an alternative technique then fusing this image to the CT scan using a suitable registration technique in order to obtain a photorealistic appearance of soft tissue.

Many techniques for 3D soft-tissue capture are now available, including biostereometrics, 3D Facial Morphometry (3DFM), laser scanning, Moiré topography, ultrasonography and stereophotogrammetry which is a promising method of photo-realistic soft-tissue capture due to its fast capture time with acceptable accuracy. In the article have validated the accuracy of 3D stereophotogrammetric images superimposition onto 3D CT images.

Unfortunately these technologies have certain limitations like the inability to standardize registration of the images over time, significant errors in head positioning and potential errors in facial expression have not been assessed. Currently, CBCT technology is used for 3D soft tissue analysis and evaluation of changes by superimposition of pre and postoperative 3D surface models.

Image-Guided Surgery (IGS) is widely used for procedures such as orthopaedic, head and neck, and neuro-surgery. The surgeons’ three-dimensional imagination is required to transform the visual information provided by CT or MRI images into spatial information about the actual anatomical situation in the surgical site. Surgical navigation assists the surgeon in transporting the pre-operative plan into the operation theatre.

For successful surgical navigation, precise point based registration is mandatory. It involves accurate spatial correlation of a patient's body position in the operation setting, the pre-operative imaging data and the intra-operative imaging data by using a three-dimensional (3D) probe whose physical position is linked to the image position through the registration transformation.

The geometric accuracy of the imaging modality used, is a prerequisite for accurate patient to image registration, and so for patients safety, and is a matter of technical image quality.

Surgical navigation has been described in a wide variety of oral and maxillofacial procedures such as operations on the skull base, paranasal sinus and orbit, to remove foreign bodies, and for orthognathic and implant surgeries (image-guided implantology). In essence it is useful in any situation where it is possible to make a three-dimensional plan for an operation, but is difficult to translate that plan during operation because of a lack of anatomical landmarks or limitation of access.

For digital subtraction, accurate registration of contrast-enhanced to unenhanced images is needed. Subtraction of post-angiography CT images and pre angiography CT images for the evaluation of peripheral arterial occlusive disease, subtraction of contrast-enhanced and unenhanced CT for the prediction of pancreatic necrosis in early stage of acute pancreatitis and subtraction of serial FLAIR MRI images for the detection of new or enlarging lesions in multiple sclerosis are examples.

A great number of medical image registration methods classifications have been proposed. In the article classified the registration methodologies by the data dimensionality (1D, 2D, 3D, 4D …), nature of the registration basis (intrinsic or extrinsic properties of patients), transformation domain (local or global), nature of transformation (rigid, affine, projective or curved), tightness
of property coupling (interpolating or approximating), parameter determination (direct or search-oriented), and interaction (interactive, semi-automatic or automatic). In the article introduced a scheme with further details to the following basic fundamental criteria: dimensionality, nature of the registration basis, nature of transformation, domain of transformation, interaction, optimization procedure, modalities involved in the registration, subject and object.

Registration between like modalities is called “intra-modal” or “monomodal” registration; registration between differing modalities is called “intermodal” or “multimodal” registration. Multimodal image registration is a complex process that needs registration methods distinct from those appropriate for monomodal registration because of the difficulty to correlate information of a different nature (anatomic and functional) and with different characteristics (spatial resolution and contrast). Multimodal image registration is needed for various applications e.g.: radiation therapy (discussed before), images fusion between anatomical modalities (CT, MRI, US) and functional modalities (scintigraphy, SPECT, PET) which together make up the nuclear medicine imaging modalities and CT and MRI images fusion as CT offers high resolution for bone structures and MR offers high contrast of the soft tissue morphology.

A rigid-body transformation is the simplest one. It allows changes in position and orientation without changing shape or size between the two scans. The procedure includes translation and rotation that preserve all distances, the straightness of lines, the planarity of surfaces and all nonzero angles between straight lines. It may be based on landmarks, semi-landmarks, curves, planes, surfaces or voxel (mutual information) to evaluate longitudinal changes.

The non-rigid transformation procedures include the similarity transformation (translation, rotation and uniform scaling), affine (translation, rotation, scaling, and shear), projective, and curved. It may be based on landmarks, elastic models, fluid models, splines and finite element models.

This type of transformation is important not only for non-rigid anatomy (almost all anatomical parts, organs, of the human body are deformable structures), but also for interpatient registration of rigid anatomy, intra-patient registration of rigid anatomy when there are non-rigid distortions in the image acquisition procedure, for modeling soft-tissue deformation during imaging or surgery and to create a composite of several different jaw shapes to guide the construction of template or standard, normal 3D surface models.

According to spatial dimensions (also named data dimensionality or image dimensionality which refers to the number of geometrical dimensions of the image spaces involved in the registration process. It is classified into: 2D-to-2D registration; used to align 2D slices from tomography data, 3D-to-3D registration; used to accurately register tomographic datasets as in registration of 3D MR and CT volumes and 2D-to-3D; done when the position of one or more 2D slices are to be established relative to a 3D volume.

Registration of images acquired during different time instances is needed to follow some process that changes with time such as; monitoring disease progress, assessment of treatment response, to study dynamic processes such as tissue perfusion, blood flow, and metabolic or physiological processes and during a radiation course for continuous target delineation and to quantify patient specific physiological motion to increase treatment accuracy and precision.

Medical Image registration can be divided according to the images aspect used to compute the registration into extrinsic method i.e., relating to external objects or markers introduced in the imaged space specifically for registration purposes, or intrinsic, i.e., based on the image information in the object under study itself which is subdivided into three categories according to: point based methods (further subdivided into marker based and landmark based methods), surface based methods and intensity or voxel based methods.

The last category (Registration basis) is our main concern in this systematic review so that it will be discussed in details.

Point based registration between images is based on a given set of point pairs that are known to correspond. These points may be normal anatomical landmarks or markers attached to the anatomy.

Landmark based registration methods are called “retrospective” or “intrinsic” methods, which is based on manual selection of anatomical landmarks on each image. It is greatly dependent on availability and visibility of the anatomical landmarks and on the ability of the user to identify those.

Marker based registration is based on objects that have been attached to the anatomy called fiducial points, or fiducials, for example, the stereotactic frame used in
image guided surgeries and point-like pins or markers attached to the skin or screwed into bone. Bone screws provide very accurate registration but are invasive and carry a risk of infection or damage to the underlying tissues. Skin markers although less invasive and safer, they are difficult to attach firmly and easily move due to the mobility of the skin.\(^5\) Registration methods that are based on such attachments are termed “prospective” or “extrinsic” methods.\(^3\)

Marker-based registration has advantage over landmark-based registration being independent of anatomy.\(^4\) It is mandatory for the markers and landmarks to be clearly visible on each scan. Identification and location of three points will be sufficient to establish the transformation between two 3D image volumes, provided the fiducial points are not all in a straight line but in practice it is usual to use more than three.\(^6\)

Surface based Registration (SBR) involves identifying corresponding surfaces in different images and approximating two surfaces by selecting corresponding landmarks on the two images then translating and rotating one of the images so the landmarks align, this is followed by application of an algorithm that compute the transformation that best aligns these surfaces by minimizing the surface distance between the two surfaces.\(^8,69,72\)

The first widely used method was the “head and hat” algorithm, but now the iterative closest point algorithm is the most widely used surface matching algorithm in medical imaging applications.\(^69,73,74\)

Surface based registration was the initial method described for 3D image superimposition.\(^2\) Compared to point based methods, it offers a more precise registration based on the fact that corresponding surfaces are composed of thousands of landmarks instead of a few landmarks selected by the user.\(^2\) However, it needs segmenting a 3D model before its application.\(^3\)

This additional step introduces human error and needs extra time in addition to that it depends on the segmentation algorithms used and the precision of the 3D surface models which in turn depend on the quality of the scan and Hounsfield value (HU value) of DICOM images.\(^2\) Further the presence of metal artifacts from metal fillings and orthodontic brackets complicate the segmentation step.\(^2\)

Voxel based registration technique is commonly known as intensity based as it depends on the voxels intensities throughout the entire selected volume.\(^5\) By comparing voxel by voxel the gray level of the images then compute the rotation and translation between data sets; it aims to achieve the least total grey scale density difference to align the two data sets to the best superimposition.\(^3,37,73,79\)

Maximizing Mutual Information (MMI); the most common voxel registration algorithm, is used in automatically computing the registration of 3D medical images. It postulates that mutual information is maximal when the images are correctly aligned. It can be applied for both intra and inter-modal registration.\(^5\)

It uses the cranial base as a stable structure to calculate rotation and translation parameters to align the two data sets.\(^4\) The cranial base models are only used to mask anatomic structures that change with growth and treatment.\(^16,76\) They are considered anatomically stable structures by age 5 as 85% of growth is completed in this area.\(^22\)

Registration using a large surface area of the cranial base gives more accurate results. For adult patients the whole cranial base surface is used for registration while for growing patients, an initial head alignment is done using the whole cranial base, and then a finer registration is performed at the stable structure on the anterior cranial base.\(^15\)

The raw information of the DICOM image is the basis of the registration in voxel based registration so it does not depend on accurate landmarks identification as in point based registration or the precision of the 3D surface models as in surface based registration.\(^2\) It is preferred to be used rather than point and surface based methods in assessing complex cases such as dentofacial deformities, severe asymmetries and skeletal displacements following different osteotomies methods in the treatment planning, during the surgical procedures as well as postoperative treatment assessment.\(^20\)

Studies reporting the use of voxel based registration have claimed high accuracy in registration.\(^71,73,79\)

The superimposition of serial 2D lateral cephalograms tracings is the standard method to quantify changes of normal craniofacial growth and treatment effects produced by various orthodontic, orthopedic, and surgical procedures.\(^73,80\)

Cone Beam Computed Tomography (CBCT) is one of the most exciting developments in dental and maxillofacial radiology. It has become a very useful and widely used technique for dentomaxillofacial imaging over the last decade. It became possible to obtain an accurate Three Dimensional (3D) representation of the patient's
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Cross-sectional cuts in axial, coronal and sagittal planes in CBCT scans permit access to the internal morphology of soft tissues and bony structures, but the localization and relationship among various facial components can be difficult to interpret. As new user friendly software tools are developed, the ability to navigate through the volumetric data set became easy.17,83

The management of CBCT images differs from that of conventional two dimensional images. Three-dimensional superimposition to evaluate and quantify growth and treatment changes is much more complicated than 2D superimposition.37

The aim of the present review is to critically evaluate the available literature with respect to the reliability of CBCT -based and CT-based registration in maxillofacial surgery.

2. Materials and Methods

This systematic review is conducted in accordance with the guidelines of the preferred reporting items for systematic reviews and meta-analysis (PRISMA) statement.

2.1 Focused Question (PICO)

In patients undergoing maxillofacial surgery, is CBCT-based and CT-based registration reliable?

2.2 Search Strategy

To search for published articles that reported on the focused questions for inclusion in the review, the electronic databases of the National Library of Medicine (PubMed-MEDLINE; Medline database, free open access of PubMed central, out of range articles, articles marked as 'epub ahead of print' and free full text articles), the Cochrane Central Register of Controlled Trials (Cochrane-CENTRAL), and the Lilacs databases were searched.

![Figure 1. Search terms for the PubMed-MEDLINE and Cochrane-CENTRAL searches and Lilacs.](image-url)

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accessed, which encompassed all available potentially relevant reports through the first of June 2016.

Search terms are shown in Figure 1. The search design sought to identify any published study that evaluated the reliability of CBCT-based and CT-based registration on maxillofacial surgeries. Searching was restricted to articles written in English. Letters, case reports, and narrative reviews were not included. The asterisk (*) was used as a truncation symbol.

3. Study Selection and Eligibility Criteria

The following eligibility criteria were imposed for inclusion in the systematic review; 1) If conducted in humans, the research was a Randomized Clinical Trial (RCT) or a controlled clinical trial; 2) studies evaluating MSCT registration and CBCT registration techniques, 3) articles concerned with registration of images from different imaging modalities were excluded, 4) articles concerned with integration of scanned dentition or digital dental models into a MSCT or CBCT scans were excluded.

3.1 Selection Strategy

The studies were screened independently by two reviewers (Helaly and Dahaba), initially by title and abstract. The full text of each possibly relevant study was retrieved and assessed by the two reviewers for inclusion and detailed assessment. If no information relevant to the eligibility criteria was available in the abstract, or if the title was relevant but the abstract was not available, the article was selected for a full reading of the text. For those articles deemed relevant, the full-text articles were evaluated by the two reviewers. All reference lists of selected studies were hand searched for additional articles that might satisfy the eligibility criteria of this review. Any discrepancies or disagreements of the two reviewers were resolved after additional discussion. If a disagreement persisted, the judgment of a third reviewer was decisive. An assessment of the methodologic study quality was performed. Criteria were designed to address each domain of internal validity, external validity, and statistical methodology.

3.3 Data Extraction

To ensure accuracy, two independent reviewers extracted the data regarding study characteristics (participants, interventions, outcomes). Any discrepancies were decided by a third reviewer. Data were extracted from the original articles where significance was presented within and between groups.

4. Results

4.1 Search and Selection

The search resulted in unique 223 publications after duplicates removal Figure 2. The screening of titles and abstracts initially resulted in 31 full-text articles. In total, 23 studies were excluded after failing the eligibility criteria after a full-text reading. Subsequently, eight studies were identified as eligible for inclusion in this review according to the defined criteria of study design, participants, intervention, and outcome judged to be relevant for this systematic review.

We found one additional study by checking the references of the relevant articles, one additional article through hand search while citations search resulted in no additional articles.

4.2 Assessment of Heterogeneity

Heterogeneity was evaluated separately for selected studies. Any or all of the following variables were used to determine heterogeneity as: study design, subject characteristics, registration technique, CBCT scanner, software, images used in registration, and outcome parameters.

4.3 Characteristics of Study Design, Participants and Intervention

Of the selected articles, only one study was comparing the accuracy of CBCT and MSCT registration (markers) for image guided surgery; in the article. Three studies were evaluating CBCT landmark registration technique; In the
presented articles. Six studies were evaluating CBCT Voxel based registration technique: In the articles. One study was comparing the accuracy of CBCT surface based registration and voxel based registration: the article.

5. Discussion

This study systematically evaluates the accuracy of CBCT-based and CT-based registration in maxillofacial surgery. A systematic review can be defined as the process of systematically locating, appraising, and synthesizing evidence from scientific studies to obtain a reliable overview.

The present review selects ten related articles. Eggers et al 2009 aimed to test the accuracy of CBCT image data for precision navigation in maxillofacial surgery compared to MSCT which is the imaging modality predominantly used in image guided maxillofacial surgery. Multiple pair-point registration using maxillary mounted template on a resin skull with fiducially markers for patient-to-image registration are used.

In the navigation world, the surgeon chooses an individual configuration of registration markers then these markers are identified in image data using a software tool, and on the patient using a tracked pointing device. This information transformation process between image space and patient space is mainly dependant on the geometric accuracy and homogeneity of the image data.

In the article concluded that registration of CBCT image data to the patient's body for image-guided surgery is possible with similar accuracy as that of MSCT inspite of the lower geometric accuracy of CBCT compared to MSCT as proven by the article.
Three studies were selected evaluating CBCT landmark based registration technique the article.\textsuperscript{1,2,5,6}

In the article worked on ten CBCT images selected from the Orthodontic Graduate Clinic database at the University of Alberta with normal upper airways in a retrospective study after ethical approval.\textsuperscript{5}

The reliability of landmarks to superimpose upper airway using CBCT images was evaluated by repeated identification and marking of the landmarks by two examiners, the first examiner marked each landmark three times one week apart and the second examiner marked the same landmarks one time only then the intra- and inter-examiner agreements were evaluated for examiner one and between both examiners, which resulted in high intra-examiner & inter-examiner reliability.

The purpose of the study was clearly stated with a good methodology in terms of good sample size, patient selection, detailed description of the performed steps and good results presentation.

In the article in a part of their study tested the reliability of landmark based registration as a diagnostic application for registration techniques in the assessment of temporomandibular joint condylar morphology.\textsuperscript{2} Across-subject and group comparisons for a sample of CBCT scan of 12 controls and 12 patients with temporomandibular joint osteoarthritis acquired for a parent study. The use of the scans was approved by the university institutional review board.

The registration was done for surface models of 48 right and left condyles constructed from CBCT Scans. Landmarks were placed on each condylar surface model, from 3-4 evenly spaced landmarks on each surface e.g. 4 points evenly spaced along the superior surface of the sigmoid notch, 4 on the medial and lateral portions of the ramus adjacent to the sigmoid notch, 3 along the posterior neck of the condyle etc. The results show high Intra-examiner & Inter-examiner reliability of the technique. The purpose of the study was clearly stated with a good methodology in terms of good sample size, patient selection, detailed description of the performed steps and good results presentation.

In the article worked on a plastic skull prepared by drilling holes as target landmarks and also dental landmarks to assess the validity of landmark based registration for image guided surgeries.\textsuperscript{6} Repeated measurements were done over time by two observers using a navigation system. They concluded that their method can be used for bimaxillary surgery to access occlusal changes during bimaxillary surgery. However, because of the observed large maximum error, clinicians should use caution when applying this registration method to other anatomical regions.

In the article showed similar methodology but differed in the population of interest.\textsuperscript{6,17} They compared the non-changing reference structures in volumetric data voxel by voxel so that this method is observer-independent, and does not rely on specific landmarks. However, this registration process lacks a clinician-friendly user interface and visualization tool, uses several different steps in various software programmes, requires extensive training, and is time-consuming (45 to 60 min), making the process unworkable for clinicians and only suitable for research but it has the advantage of using a readily available open-source software programmes instead of other softwares that are only available commercially e.g. OnDemand 3D.

In the article worked on CBCT scans taken before and after orthognathic surgery for ten patients with various malocclusions undergoing maxillary surgery only to assess changes due to surgical procedures after approval of the Institutional Review Board of the University of North Carolina.\textsuperscript{12}

After segmentation, the pre and post-surgery models were registered using voxel-wise rigid registration based on the cranial base surface, as the cranial base structures are not altered by the surgery then surface distance calculation at the posterior border and at the condyle were measured using colour-coded maps.

In the article worked on CBCT scans taken before and after Class III malocclusion orthopedic treatment with miniplates for three growing patients (mean age, 11.4 years) after approval of the Institutional Review Board of the University of North Carolina.\textsuperscript{14} After segmentation, the pre- and post-surgery models were registered using voxel-wise rigid registration based on the cranial base surface, as the cranial base complete growth by age 7, and then displacements relative to the cranial base at nine anatomic regions were measured using colour-coded maps.

The authors of both studies concluded that the technique is valid and reproducible for 3D assessment of craniofacial structures to identify treatment outcomes following orthognathic surgery in the article presented.
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and for 3D assessment of growing patients and treatment outcome in the other presented article based on the results that the range of the interobserver errors as well as interobserver variability was negligible. The weakness of the studies is in the small sample size used and the use of color maps as previously described.2,16,17

Only one study was found evaluating the accuracy of voxel based registration.22 The difference between their work and the work done by the article is that evaluated the reliability as well as the accuracy of voxel registration.2,16,17,21

They evaluated the voxel based registration in a retrospective study using a pre-operative and eighteen months post-operative CBCT images of sixteen adult dysgnathic patients retrieved from the Radboud University Nijmegen Medical Centre CBCT database after ethical approval. They reported that it took 30 to 40 min to complete a single superimposition of two longitudinal CBCT volumes. The technique reliability was tested by measuring the intra-observer and interobserver variability which was very small or insignificant. This is in accordance with the results of the articles.2,16,17

Repeated measurements were made over time and actual values are reported (e.g., means, standard deviations, proportions), not just the results of statistical tests. The technique accuracy was tested by measuring the mean absolute distances between the preoperative and postoperative models at certain anatomic areas (the anterior cranial base, the forehead, left and right zygomatic arches) based on the fact that these areas are stable structures that show no change following orthognathic surgery. The results showed Voxel based image registration could be considered as an accurate method for CBCT superimposition.

In the article investigated the accuracy of image fusion based on Maximum Mutual Information (MMI) algorithm which is the most commonly used algorithm as previously described using 24 CBCT 3D images of a human skull with different head positions and mandibular occlusions fused onto a standard CBCT skull image.24 The location of the titanium markers was assessed by two examiners, and the distance between the markers was calculated using 3D coordinates system. The superimposition mean error was 0.39 mm (±0.142 mm) and there were no significant differences in the dry skull superimpositions. Although they did not evaluate the accuracy of longitudinal CBCT superimposition for growing patients and used the whole cranial base as reference instead of the anterior cranial base, the superimposition results were similar.

Voxel registration reliability was also evaluated in the other part of the article as a technique used for assessment of growth, progression of disease, treatment outcome and stability after treatment.2 Longitudinal assessments for a sample of CBCT scans of 12 patients with temporomandibular joint osteoarthritis, followed up at pre-operative jaw surgery, immediately after and one-year post-operative. The results showed high Intra-examiner & Inter-examiner reliability of the technique.

In the article aimed to evaluate a fast method (10–15s) for 3D superimposition of CBCT volumes which make it rapid, and applicable for research and clinical practice in growing patients and adults (surgical cases).22 For 10 patients, as the gold standard, the spatial position of the pretreatment CBCT was reoriented, saved as a reoriented volume, and then superimposed on the original image. For eight patients, four non-growing and four growing, the pre- and post-treatment scans were superimposed.

This study validated the superimposition method introduced by the article for voxel-based registration. The superimposition error of the spatial reorientation and for growing and non-growing patients was <0.5 mm, which is acceptable and clinically insignificant.24

The advantages of this method include its rapidity (takes about 10 to 15s), having a user-friendly software interface, not requiring extensive training, using only one software programm, and being easily used by the clinician. Additional advantages of the method presented include the facts that the CBCT volume superimpositions are fast, even when the CBCT scans have small voxel sizes (0.25 mm) and high spatial resolution, and the registration process does not require previous segmentation to designate the area of superimposition. Also, CBCT superimpositions with registration at areas outside the cranial base are possible and can potentially be applied for regional superimpositions.

The weakness of the studies is in the small sample size used and the use of color maps as previously described.

Only one study was found comparing different registration techniques.22 They compared the accuracy of surface based registration and voxel based registration in a retrospective study using pre-operative and six months post-operative CBCT images of thirty one patients randomly selected from the orthognathic patient database at the Dental Hospital and School, University of Glasgow, UK after ethical approval. After models segmentation,
surface registration and voxel registration; evaluation of registration accuracy was done by measuring the mean value of the absolute distance between the preoperative and the postoperative image surfaces. The purpose of the study was clearly stated with a good methodology in terms of acceptable number of patients, detailed description of the performed steps of images superimposition and actual values were reported (e.g., means, standard deviations, proportions), not just the results of statistical tests. The conclusions were justified from and supported by the results that there was no significant statistical differences between the two registration methods and that surface based registration was associated with higher variability than voxel based registration.

The authors attributed this variability of SBR to the following reasons: 1-Surface based registration requires an extra step of 3D surface model generation on which the surface based registration is performed which may introduce a possible source of error since the algorithm used for segmenting the 3D model depends on the Hounsfield value (HU value) of DICOM images of the CBCT. 2- The form and dimension of the 3D surface model is dependent on the HU value which in turn may be affected by image quality and tissue density. 3- Surface based registration uses the 3D information provided by surface mesh topography of the 3D model, whereas voxel based registration uses the grey scale values of all the voxels in the DICOM image volume which may theoretically increase the accuracy of the method. 88,89

6. Conclusion

The reliability and accuracy of different registration techniques has frequently been evaluated individually and less frequently comparing their accuracy and efficacy. This systematic review of a large body of published research in the preceding two decades consistently showed many registration techniques in maxillofacial surgery to be reliable but only one study compared the efficacy of the different registration techniques. It is recommended that future investigations should include comparisons between different registration techniques.

7. References

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