Novel CBCT-MRI Registration Approach for Enhanced Analysis of Temporomandibular Degenerative Joint Disease *

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Abstract. Temporomandibular Degenerative Joint Disease (TM DJD) is characterized by chronic and progressive degeneration of the joint, leading to functional limitations. Converging on enhancing TM DJD diagnosis, prognosis, and personalized patient care, multimodal Cone Beam Computed Tomography (CBCT) and Magnetic Resonance Imaging (MRI) registration aims to allow comprehensive understanding of the articular disc and subchondral bone alterations towards elucidating the onset, advancement, and progression of TM DJDs. This study proposes a novel multimodal image registration (fusion) approach that combines image processing techniques with mutual information to register MRI to CBCT images, enhancing TMJ complex visualization and analysis. The algorithm leverages automated image orientation, resampling, MRI inversion, normalization and rigid mutual information registration methods to align and overlay multimodal images while preserving anatomical details. Evaluation on 70 CBCT and 70 MRI scans acquired at the same time points for 70 TM DJD patients demonstrates robustness to variations in image quality, anatomical morphology, and acquisition protocols. By integrating MRI soft tissue information with CBCT bony details, this novel open-source tool available in the 3D Slicer platform provides a more comprehensive patient-specific TM DJD model. The current 98.75% success rate, with mean absolute rotation differences of 1.53° ± 1.75°, 1.69° ± 1.54°, and 2.70° ± 2.89° in Pitch, Roll and Yaw respectively; and translation differences of 0.92mm ± 1.64mm, 0.98mm ± 0.85mm, and 0.5mm ± 0.43mm in respectively the Left-Right, Antero-Posterior and Supero-Inferior axes. The proposed approach has potential to enhance care for TM DJD and other conditions requiring multimodal images.

Keywords: Multimodal image · Fusion · Degenerative joint disease

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1 Introduction

Temporomandibular joint (TMJ) disorders are complex conditions affecting the jaw joint and surrounding tissues [1]. Accurate diagnosis and treatment planning require detailed visualization of both bony structures and soft tissues, including the articular disc, ligaments, and musculature. Cone-beam computed tomography (CBCT) is widely used in dental and maxillofacial imaging due to its high spatial resolution and relatively low radiation dose [2]. However, CBCT has limited soft tissue contrast and cannot adequately visualize the disc and surrounding tissues crucial for TMJ assessment [3].

Magnetic resonance imaging (MRI) provides superior soft tissue delineation without ionizing radiation, making it an ideal complement to CBCT for comprehensive TMJ evaluation [4, 5, 6]. Integrating MRI and CBCT data represents a significant advancement in craniofacial assessment, offering unprecedented diagnostic accuracy and treatment planning precision [6, 7].

Despite the recognized value of utilizing both modalities, integration remains challenging due to differences in patient positioning, image resolution, and field of view. Traditional registration algorithms are less effective due to the inherent differences in information provided by each modality, necessitating advanced, automated solutions to ensure accurate and efficient data fusion [8]. Manual registration is time-consuming and prone to inter-observer variability [7].

This study aims to address these limitations by developing an algorithm for automated MRI to CBCT registration, enabling efficient and accurate fusion of the complementary information provided by each modality. The novel approach employs image processing methods to achieve robust alignment and natural-looking integration of the multimodal images. By providing a holistic 3D model of the patient's TMJ anatomy [9, 10], this technique has the potential to greatly enhance diagnostic capabilities and facilitate personalized treatment strategies.

2 Materials

A total of 70 CBCT and 70 MRI scans of the head in Digital Imaging and Communications in Medicine (DICOM) format were used in this work. The images were acquired at different clinical centers with different scanners, acquisition protocols, and fields of view. All DICOM files were anonymized removing all identifiable personal information using the 3D Slicer Batch Anonymizer module. The University of Michigan Institutional Review Board (IRB) HUM00239207 waived the requirement for informed consent and granted IRB exemption. The CBCT and MRI scans were acquired using standard clinical protocols without any additional imaging performed for research purposes. All images were anonymized and stripped of protected health information prior to being transferred to the researchers. The data was securely stored on encrypted servers with access restricted to authorized personnel only.

3 Methods

3.1 Data Preprocessing

To achieve accurate registration of MRI to CBCT scans, we developed a novel pipeline that combines both newly developed automated procedures and previously developed tools. The overall workflow of the MR2CBCT registration process is illustrated in Figure 1. Initially, the CBCT files were not oriented because of the inconsistency in imaging acquisition protocols, patient position during image acquisition, and settings used on scanners in different clinical centers [11]. Therefore, the first step involved orienting and centering these CBCT scans to a common frame of reference. To do this, we used Automated Orientation available on 3DSlicer [12]. Similarly, the MRI data required orientation and centering to align with the CBCT scans.

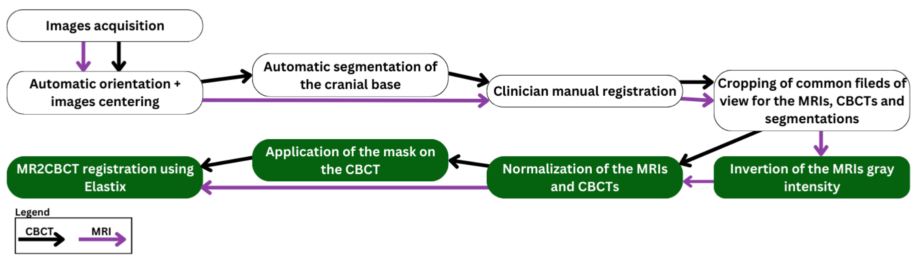

Fig. 1. Workflow of the MR2CBCT registration. The proposed novel pipeline consists of both new automated procedures (shown in green) and previously available tools (shown in gray) that are leveraged to build the overall registration workflow.

Following this, a clinician expert performed a manual registration using the 3D Slicer Transforms tool to register the CBCT scans with the MRI scans. This manual alignment was essential to establish an initial correspondence between the two modalities. Once the initial registration was achieved, a consistent bounding box was used to crop both the CBCT and MRI scans around the temporomandibular joint (TMJ) area, which was the primary region of interest for our analysis. The machine learning models for CBCT segmentation of the cranial base were automatically computed using the tools called AMASSS [13] from the 3D Slicer 5.6.2 and used as stable regions of reference for registration. The MRI images underwent inversion of the gray level intensity values to better match the contrast of the CBCT scan, as MRI and CBCT images typically present different intensity distributions (Figure 2). After inversion, we normalized the intensity values of the MRI and CBCT images to a common range, typically [0, 100] for MRI and [0, 75] for CBCT, to ensure consistent intensity scales over the regions of interest in our two images. The preprocessed images were then saved and used in the registration process.

3.2 MRI to CBCT Registration (Fusion)

Following the clinician's manual registration and preprocessing steps, the Elastix mutual information rigid registration method was applied to refine the alignment between the MRI and CBCT scans [14]. The steps involved in this process were:

Mask Application: The mask obtained from the segmentation of the CBCT was applied to the preprocessed CBCT image, isolating the cranial base region to serve as a stable reference for registration with the MRI. This step ensures that the registration focuses on the most relevant anatomical structures and reduces the influence of noise or artifacts in other regions.

Rigid Registration: The rigid registration approach in Elastix optimizes the transformation parameters, including translation and rotation, to achieve the best overall alignment between the two imaging modalities. Unlike non-rigid methods, this approach maintains the original geometry of the images, which is particularly important for preserving anatomical relationships. The rigid registration allows for correction of global misalignments, improving the overall spatial correspondence between MRI and CBCT.

Optimization: Elastix utilizes an optimization algorithm to iteratively adjust the transformation parameters to maximize the mutual information between the images. Mutual information is a statistical measure that quantifies the amount of information obtained about one image given the other, making it suitable for multimodal registration. The optimization process seeks to find the transformation that results in the highest mutual information, indicating the best alignment between the MRI and CBCT scans.

Transformation Parameters: The optimized transformation parameters, including the translation and Euler angles (rotation), were extracted and analyzed to quantify the registration accuracy in six degrees of freedom (DOF). These parameters provide a quantitative measure of the registration performance and can be used to assess the reliability of the registration results.

The Elastix mutual information rigid registration approach leverages the strengths of both imaging modalities, combining the soft tissue contrast of MRI with the bony detail of CBCT. By iteratively optimizing the transformation parameters to maximize mutual information, this method aims to achieve a more precise and robust alignment compared to manual registration alone. The application of the CBCT segmentation mask aims to enhance the registration accuracy by focusing on the most stable and relevant anatomical regions. The goal of this approach is for the resulting registered images to provide a comprehensive 3D model of the TMJ, enabling improved visualization and analysis of both soft tissue and bony structures.

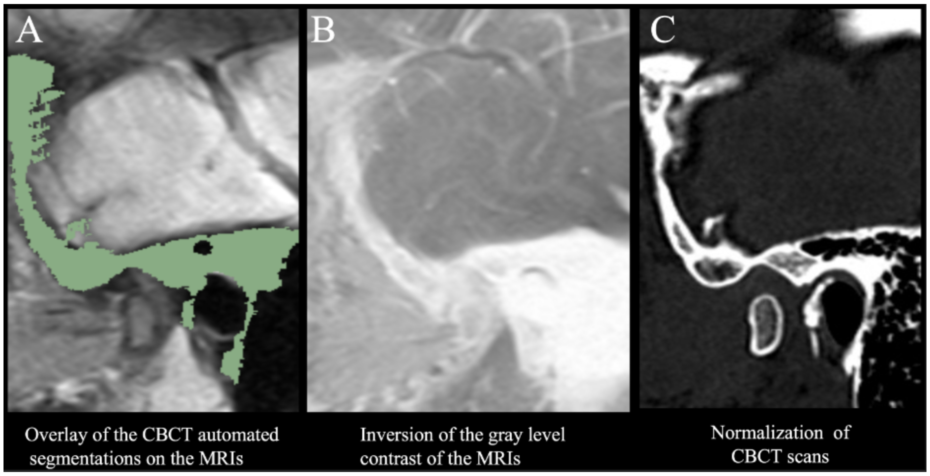

Fig. 2. Preprocessing steps for MRI-CBCT registration. (A) Overlay of the automated CBCT segmentation (shown in green) on the MRI scan, highlighting the cranial base as a stable region of reference. (B) Inversion of the gray level contrast of the MRI scan to better match the intensity characteristics of the CBCT scan, facilitating the registration process. (C) Normalization of the CBCT scan to achieve consistent intensity scales over the regions of interest between the MRI and CBCT images.

3.3 Evaluation Metrics

To quantify the quality of registration between MRI and CBCT images, a multi-step approach was employed. Initially, a clinician performed manual registration to align the MRI with the CBCT using the 3D Slicer Transforms module, providing a baseline for comparison. We then calculated the registration matrices for the whole sample using the Elastix mutual information rigid registration. The voxel-based registration was quantitatively assessed in the six degrees of freedom of the translation (Left-Right, Antero-Posterior and Supero-Inferior axes) and rotation (Pitch, Roll, and Yaw axes). Summary statistics were computed in Jamovi software version 2.3.28 to report for the differences in each degree of freedom, including the mean difference, mean absolute difference, minimum and maximum absolute differences, and 75th and 90th percentiles of the absolute differences, and graphically display the errors distribution. The quality of voxel-based registration was verified through visual inspection by an expert clinician. The clinician's quality control check focused on the alignment of key anatomical structures and overall spatial correspondence between the two imaging modalities. This quality control allowed detection of clinically relevant registration improvements not captured by the quantitative metrics. Cases were classified as successfully registered if they demonstrated clear visual improvement over the clinician manual registration and if the linear differences in the MR translation were less than 4 mm relative to the CBCT. Adjustment of the MRI normalization parameters was used to improve the precision of the MRI registration to the

CBCT. As a gold standard, a panel of expert clinicians reviewed the results after the method was applied, providing a final validation of the registration quality.

4 Results

The registration method was applied to a dataset of 70 MRI-CBCT image pairs. The transformation matrices were then evaluated for quality control by an expert clinician, and the variability of the six degrees of freedom was assessed by comparing the automated registration results to the clinicians' gold standard registration (Table I and Figure 3).

ROTATION (°)			
	Pitch	**Roll**	**Yaw**
Mean difference (SD*)	0.49 (2.28)	-0.62 (2.21)	-0.99 (3.84)
Mean absolute difference (SD*)	1.53 (1.75)	1.69 (1.54)	2.70 (2.89)
Minimum absolute difference	0.00	0.02	0.03
Maximum absolute difference	8.72	6.79	16.60
75th percentile of absolute difference	1.93	2.56	3.04
90th percentile of absolute difference	3.51	3.32	5.10
TRANSLATION (mm)			
	LR	**AP**	**SI**
Mean difference (SD*)	0.3 (1.86)	0.89 (0.94)	-0.20 (0.63)
Mean absolute difference (SD*)	0.92 (1.64)	0.98 (0.85)	0.50 (0.43)
Minimum absolute difference	0.01	0.01	0.00
Maximum absolute difference	13.10	3.52	2.57
75th percentile of absolute difference	1.16	1.48	0.72
90th percentile of absolute difference	1.55	2.12	0.95

* Abbreviation of Standard Deviation (SD)

Table 1. Differences in six Degrees of Freedom between clinician and Elastix Image Registration.

The results indicate small differences, with mean absolute rotation differences of 1.53°, 1.69° and 2.70°, respectively in Pitch, Roll and Yaw, and mean absolute translation differences of 0.92 mm, 0.98 mm and 0.50 mm respectively in the Left-Right, Antero-Posterior and Supero-Inferior axes. Sixty-nine out of 70 cases presented less than 4 mm in the MRI translation in each axis relative to the CBCT compared to the clinician manual registration. Eleven cases whose MRIs presented darker gray level intensity had a difference of MR translation >2mm and <4mm. Fifty-two cases presented less than 2 mm in the MR translation in each axis relative to the CBCT compared to the clinician manual registration, with improved MRI to CBCT image registration in the clinician quality control check (Figure 4). The sequence of image processing steps for images centering, orientation, resampling, MRI inversion, normalization and Elastix mutual intensity registration of MRI to CBCT were deployed in Github as a 3D Slicer module for multimodal registration called MR2CBCT.

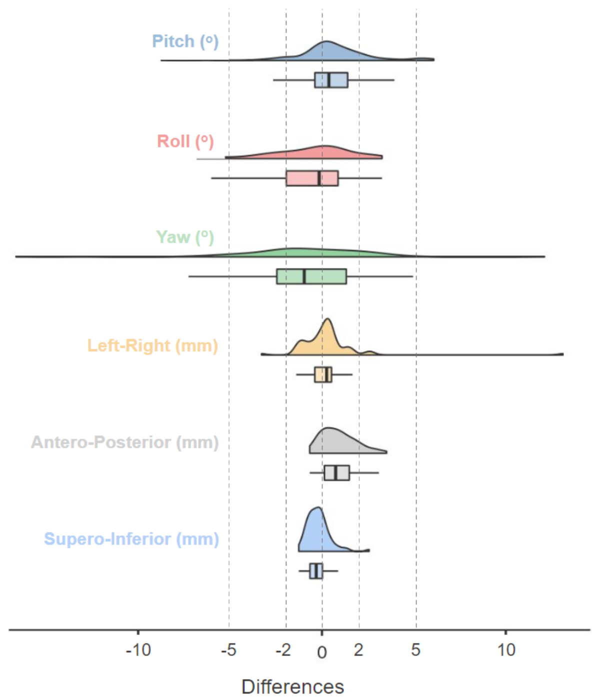

Fig. 3. Box plots with overlaid density plots showing the differences in six degrees of freedom (Pitch, Roll, Yaw, Left-right, Antero-posterior, and Supero-inferior) between the clinician registration and the Elastix registration approaches. The boxes represent the interquartile range (IQR) between the 25th and 75th percentiles, with the median marked by the horizontal line inside the box. The whiskers extend to the most extreme data points within 1.5 times the IQR from the box edges. Outliers beyond the whiskers are plotted as individual points. The density plots on either side of the boxes illustrate the distribution of the data points, with the width of the shaded area representing the proportion of data at each value. Positive and negative values indicate the direction of differences between the clinician and Elastix registration approaches.

5 Discussion

The present study introduces a novel automated method for registering MRI to CBCT scans, focusing on the TMJ region. The proposed approach addresses the limitations of existing methods by integrating image processing techniques to perform robust and accurate multimodal image registration. The results demonstrate the effectiveness of the developed pipeline in aligning MRIs and CBCTs, enabling the fusion of complementary information provided by each modality.

Our study underscores the critical importance of thorough preprocessing in achieving accurate MRI-CBCT registration. The initial steps of orientation, centering, and manual approximation proved fundamental in establishing a common frame of reference, addressing a key challenge in multimodal imaging [11, 12].

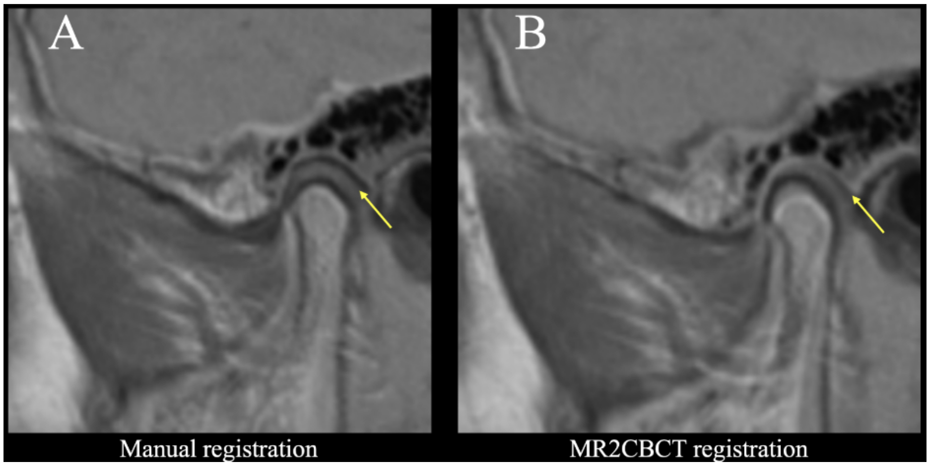

Fig. 4. MRI-CBCT Overlays: (A) Manual registration; (B) Post MR2CBCT Registration using the Cranial Base as a stable region of reference. Note that the CBCT was taken with the mouth slightly open which may have been challenging for the clinician performing manual registration; also note how the fit of the cranial base was improved in the mutual information registration performed by the MR2CBCT algorithm in B.

By utilizing the Automated Orientation tool in 3D Slicer and incorporating clinical expertise, we were able to overcome the inherent differences in image acquisition between MRI and CBCT. The focused cropping of the TMJ area not only streamlined the registration process but also enhanced its precision by concentrating on the most relevant anatomical structures.

The segmentation of the cranial base in CBCT images provided stable reference regions, improving the reliability of the registration process. Our image enhancement techniques, including the inversion of MRI gray level intensities and normalization of both MRI and CBCT images, played a vital role in bridging the gap between the two imaging modalities [7, 10]. These preprocessing steps significantly facilitated the identification of corresponding anatomical features across modalities, addressing a persistent challenge in multimodal registration.

When considering differences between the gold standard and Elastix registrations, the smallest linear displacement errors were observed in the supero-inferior direction, while the greatest in antero-posterior direction. Regarding rotational differences, the largest error was in pitch. These findings are similar to the directions of greater differences in automated orientation and registration for multiple CBCT scans tested previously [12]. Although these errors can be minimized by future research, they are already within a clinically acceptable range.

Successful integration of MRI and CBCT scans has profound implications for TMJ disorder diagnosis, treatment planning, and research. By providing a holistic 3D model of TMJ anatomy, including both hard and soft tissues, clinicians can gain a more comprehensive understanding of underlying pathologies [3, 6]. This enhanced visualization enables identification of subtle changes in articular disc, ligaments, and musculature, invisible on CBCT alone, guiding personalized treatment strategies [8]. The proposed method also has potential to advance TMJ disorder research, opening new opportunities for large-scale studies investigating etiology, progression, and treatment outcomes [1, 2].

Despite the insights gained, this study has some limitations. Eleven cases with darker MRI gray level intensity presented a difference of MR translation $>$2mm and $<$4mm. Although they were considered successful cases, there is still space for further refinement of preprocessing techniques to handle varied image qualities. Future studies should validate the proposed method on larger, more heterogeneous datasets to assess generalizability. Establishing target points on both MRI and CBCT images or creating MRI segmentations would allow us to incorporate quantitative metrics like Target Registration Error (TRE) and Dice Similarity Coefficient. This future addition will provide a more comprehensive evaluation of registration quality [7].

The proposed automated registration method demonstrates high success rates and has the potential to significantly enhance diagnosis, treatment planning, and research. The comprehensive preprocessing pipeline, combined with the rigid registration approach, enables accurate alignment of MRI and CBCT, providing a holistic 3D model of TMJ anatomy. The proposed pipeline was tested and implemented as functionalities of a free open-source module (available at https://github.com/DCBIA-OrthoLab/SlicerAutomatedDentalTools) with a user-friendly interface in 3DSlicer. Future work should focus on further refinement of preprocessing techniques, quantitative comparisons with various registration approaches as well as incorporate automated segmentation of the articular disc to improve the robustness and clinical applicability of the proposed method.

6 Conclusion

The novel MRI to CBCT registration method developed in this study represents a significant advancement in multimodal image fusion for TMJ disorders. The proposed approach integrates state-of-the-art image processing techniques to enable accurate and efficient alignment of MRI and CBCT scans, providing a comprehensive 3D model of the patient's TMJ anatomy. The results demonstrate a high success rate and small mean absolute differences in rotation and translation, indicating the robustness of the registration approach. This holistic visualization has the potential to enhance diagnostic capabilities, facilitate personalized treatment planning, and advance research in the field of TMJ disorders

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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