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Original Article

Craniofacial soft and hard tissue symmetry depicted with MRI, based on integrated and modular organization of the human head: three-dimensional analysis

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Abstract: Purpose: Accurate evaluation of craniofacial symmetry is crucial but challenging in orthodontic practice. We propose a 3-dimensional analysis of the craniofacial general contour and details of the soft and hard tissue symmetry using magnetic resonance imaging (MRI). Methods: For this purpose, recently described black bone and soft tissue MRI sequences were taken of a volunteer and analyzed using a coordinate system. Because various craniofacial tissues (brain-skull-face and nerve-bone-muscle) are interactive structures, brain midline and facial midline are highly consistent. The anterior cerebral falx (falx cerebri) was used as a median sagittal plane in this coordinate system. The newly proposed method of obtaining MRI data via black bone and soft tissue sequences can be analyzed using the coordinate system. Results: The coordinate system can be transferred between soft tissue and black bone sequences to provide an accurate analysis of craniofacial features in 3 dimensions for determination of craniofacial asymmetry. Conclusion: This preliminary study presents new ideas and methods for the 3-dimensional analysis of craniofacial symmetry, determination of the median sagittal plane, and avoiding radiation.

Keywords: MRI, orthodontic, cerebral falx, craniofacial features

Introduction

The increased demand for improvement in facial aesthetics has greatly focused on craniofacial symmetry [1]. The accurate evaluation of facial asymmetry is crucial but challenging in orthodontic practice. In recent years, cone beam computed tomography (CBCT) has been used widely for various clinical applications in dentistry [2, 3]. CBCT provides accurate and comprehensive 3-dimensional (3D) images of dental tissues [4, 5].

However, there is no widely accepted method to evaluate craniofacial asymmetry in 3D. This is because establishing a midline reference plane is especially important, and while methods for determining the median sagittal plane have been reported [6-11], each is limited in some way. A second consideration is that obtaining a reference database using computed tomography (CT) or CBCT imaging presents ethical issues related to ionizing radiation [12].

To explore acceptable methods to analyze craniofacial asymmetry, we reviewed the scientific literature [13-16] in the fields of clinical medicine, evolutionary development, and underlying molecular biology. We noted that various tissues such as the brain, skull, face, nerves, bones, and muscles are mutually interactive [17-19]. These tissues may be perceived as an integrated and modularized system that has evolutionary antecedents. Soft tissues such as muscles have a vital role in the occurrence, development, and treatment of craniofacial malformations [20, 21]. Therefore, it is of great significance to evaluate the soft tissue in determining craniofacial asymmetry.

Table 1. MRI scanning parameters (T1, 3D BRAVO) used for the black bone and soft tissue sequences

	Black bone	Soft tissue
Repetition time, ms	9.3	8.3
Echo time, ms	4.2	3.2
Flip angle, degree	5	13
Slice thickness, mm	1.2	1.2
Phase encode	256	256
Frequency encode	256	256
Zero filling interpolation	1024	1024
Number of excitations	2	2
Echo train length	1	1

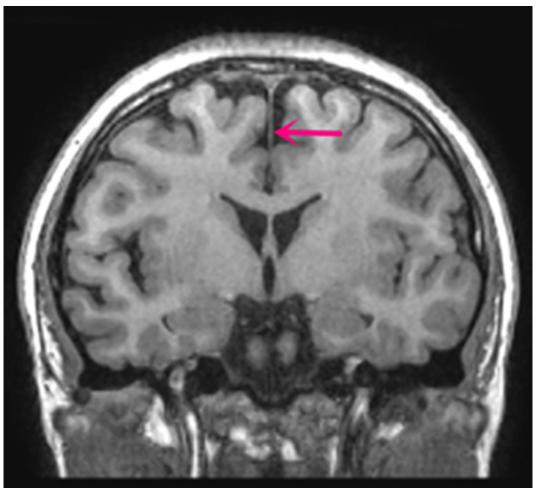

Figure 1. A representative MRI image of the cerebral falx in one frontal plane of a soft tissue sequence. The boundary between the cerebra falx and brain parenchyma is clearly delineated (arrow), so it is convenient to position the cerebra falx in the soft tissue sequence.

The brain and facial midlines are highly consistent [13, 22-30]. We propose a new method to analyze facial asymmetry in 3 dimensions using the midline of the brain (anterior cerebral falx or falx cerebri) as a median sagittal reference plane.

Magnetic resonance imaging (MRI) is mainly used for evaluating soft tissue structures, particularly the brain. Attempts at segmentation of the bone of the craniofacial skeleton have been limited. Recently, Eley and colleagues [31-33] described an MRI sequence referred to as "black bone" for imaging cortical bone, and advocated its use as a potential non-ionizing alternative to CT. Black bone MRI can also be considered a potential method for cephalomet-

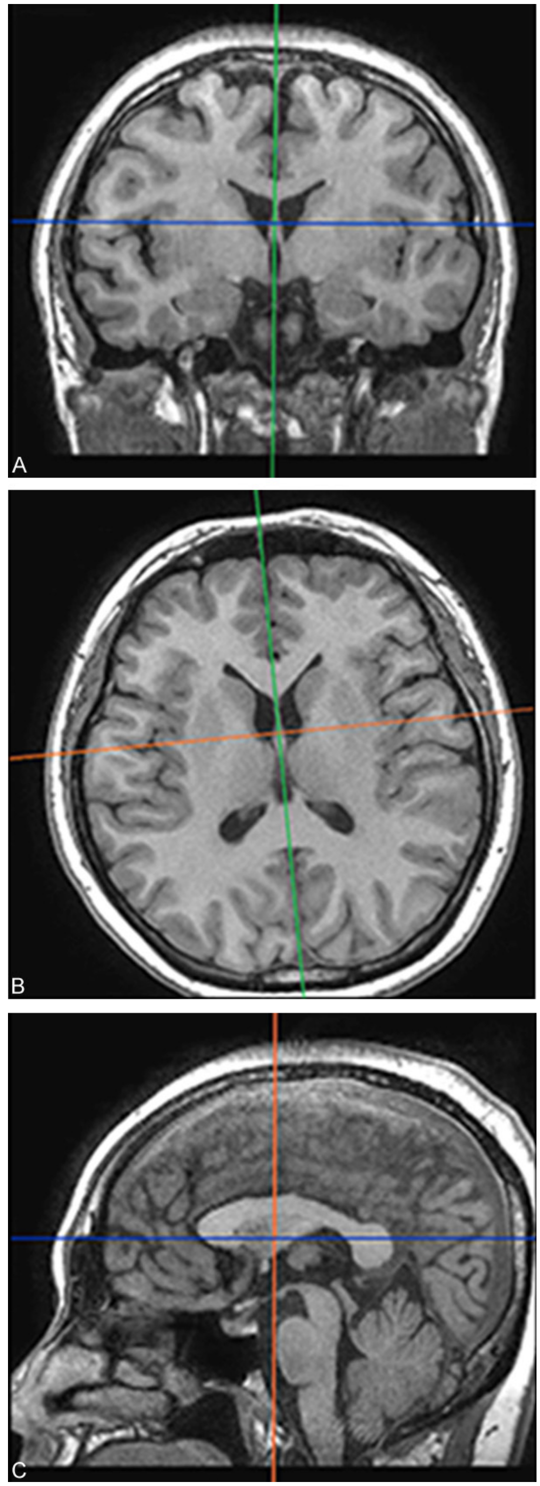

Figure 2. MRI soft tissue sequence of the cerebral falx median sagittal plane. (A) coronal, (B) axial, and (C) sagittal planes. The green line completely coincides with the cerebral falx in the coronal and axial planes. In this 3D coordinate system, the blue and orange lines automatically change their position in relation to green line movement, while remaining perpendicular to each other. The blue and orange lines represent the horizontal and coronal planes, respectively.

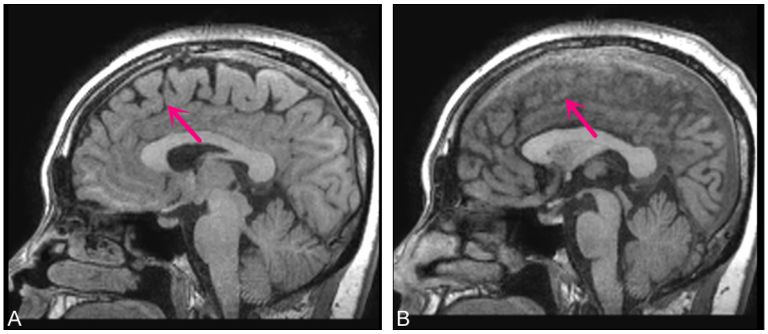

Figure 3. Comparison of MRI sagittal image of brain parenchyma and cerebral falx. A. Sagittal image of brain parenchyma showing gyri and sulci (arrow). B. Sagittal image of cerebral falx appearing like a thin film (arrow).

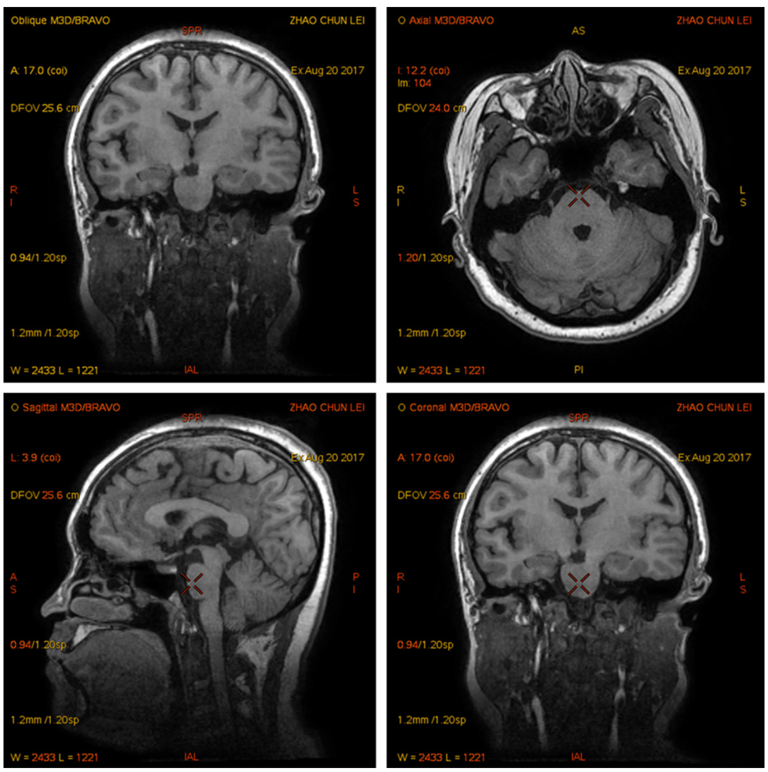

Figure 4. Enter the black bone and soft tissue data into the reformat program, then select "soft tissues" for the 3D images of soft tissues.

ric 3D analysis. As various tissues of the human head are interactive, the role of muscles in the development of craniofacial asymmetry has attracted much attention [8, 34]. MRIs of both soft and hard tissue can enable clinicians to diagnose craniofacial asymmetry without exposing patients to unnecessary radiation.

Therefore, we propose here a new method to analyze, in 3D, the craniofacial contour and details of soft and hard tissue symmetry using MRI. For this purpose, MRI black bone and soft tissue sequences of a human volunteer were analyzed using the coordinate system. We used the anterior cerebral falx as the median sagittal plane in this coordinate system. The cerebral falx is a dura mater separating the cerebral hemispheres and can be easily visualized in the soft tissue MRI sequence. The symmetry of the region of interest (ROI) is most clearly depicted by changing the position of the origin and the horizontal plane relative to the unchanged falx median sagittal plane.

Methods

A healthy woman volunteer (aged 32 years) provided informed written consent to MRI soft tissue and black bone scanning and agreed to participate in the study (**Table 1**). The MRI scanning was performed at the Department of Imaging, Tongliao City Hospital, Tongliao, China using a 1.5 Tesla system (GE Medical System, Signa HDxt). The volunteer was in the conventional position for imaging the head, with her teeth in centric occlusion. Scanning was performed using an 8NV-head coil. The imaging data was analyzed using a computer software Advanced Workstation (V 4.6 GE Medical Systems, Buc, France).

Results

In the MRI soft tissue sequence, the cerebral falx was clearly observed (**Figure 1**). The cerebral falx adjacent to the occiput (posterior) has a different embryonic origin and deviates from the midline. Therefore, the portion of the cerebral falx that is anterior to the hypophyseal foramen is considered the median sagittal plane.

The 3D localization of the cerebral falx median sagittal plane was seen in the soft tissue sequence (**Figure 2**). After coronal and axial positioning of the cerebral falx, its accuracy

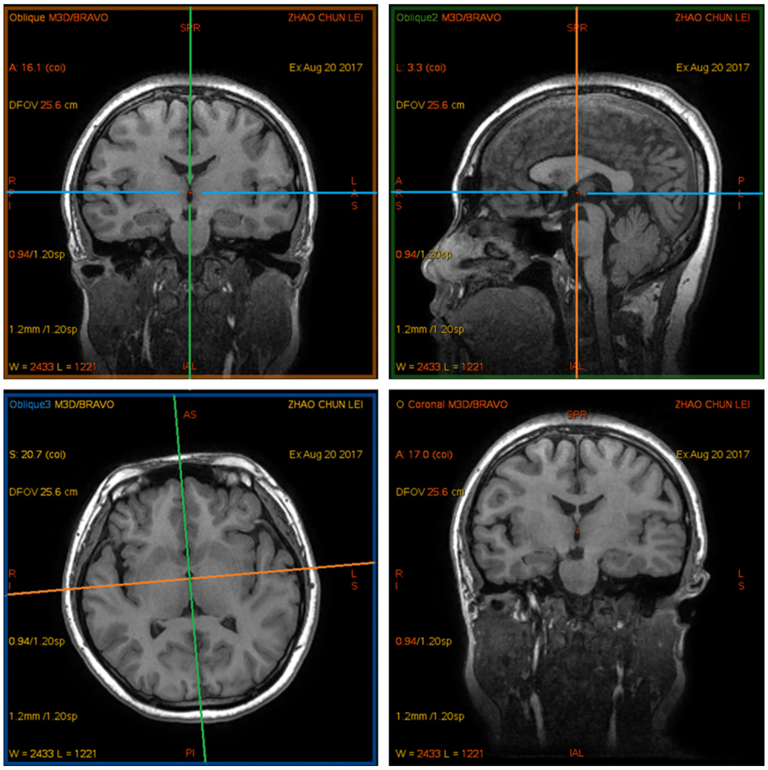

Figure 5. Three-dimensional localization of the cerebral falx plane in soft tissues sequence as shown in **Figure 2**.

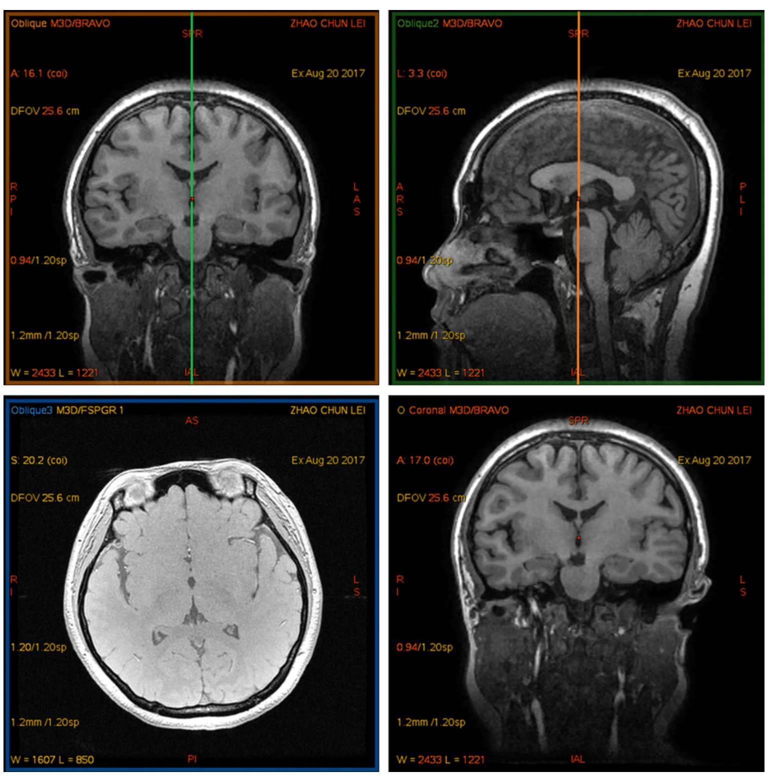

Figure 6. The image of the left bottom window that has been transferred to the black bone sequence.

could be verified in the sagittal plane. If the coronal and axial positioning of the cerebral falx is correct, the cerebral falx in sagittal images appears as a membrane rather than a brain fold (**Figure 3A**, **3B**). The cerebral falx plane is more easily located in the soft tissue sequence compared with the black bone sequence. Therefore, we studied the symmetry of the craniofacial soft and hard tissues by transferring the cerebral falx plane from the soft tissue sequence to the black bone sequence.

The cerebral falx plane can be freely transferred between the soft tissue and black bone sequences as required. The procedure is as follows. First, the black bone and soft tissue data is entered into the reformat program (**Figure 4**). Then, the multi-oblique function is used to enter the 3D coordinate system. The cerebral falx plane in the soft tissue sequence is located in 3D (**Figure 5**). Finally, the cerebral falx median sagittal plane, positioned in the soft tissue sequence, is converted to the black bone sequence (**Figures 6**-**11**). The location of the cerebral falx median sagittal plane does not change, and we can analyze the symmetry of the soft and hard craniofacial tissue using the same plane as the reference.

Using the cerebral falx as the median sagittal reference plane, we selected the position of the origin (which can be any point in the cerebral falx median sagittal plane). We then selected the horizontal or frontal plane, which is the clearest display of the symmetry of the ROI. We thus can observe

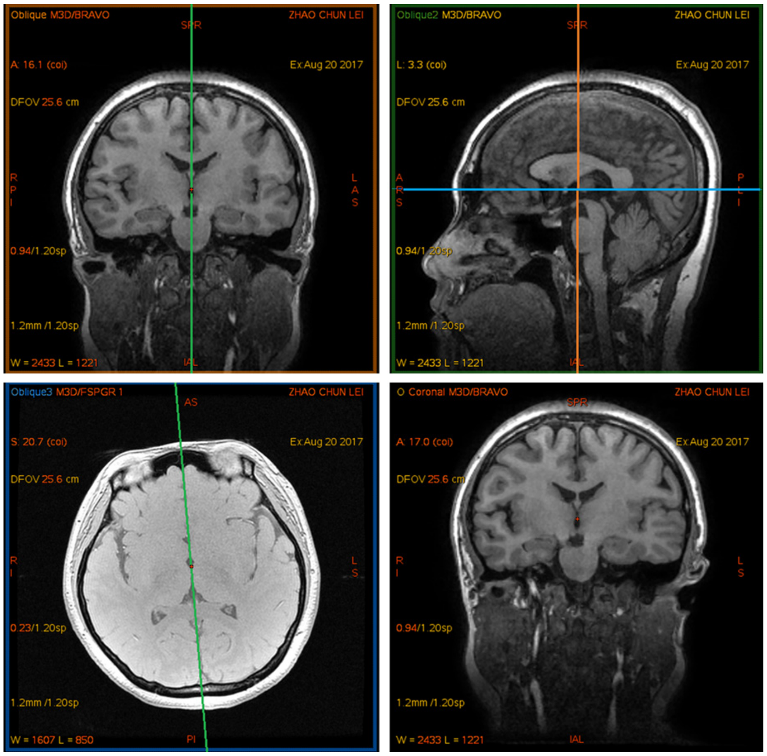

Figure 7. The top-right window selected (Step 2), the median sagittal plane (the green line) has been transferred to black bone sequence. This coincides with the falx median sagittal plane in the black bone sequence. However, it is easily and accurately positioned in the soft tissue sequence (as shown in **Figures 1**, **2**).

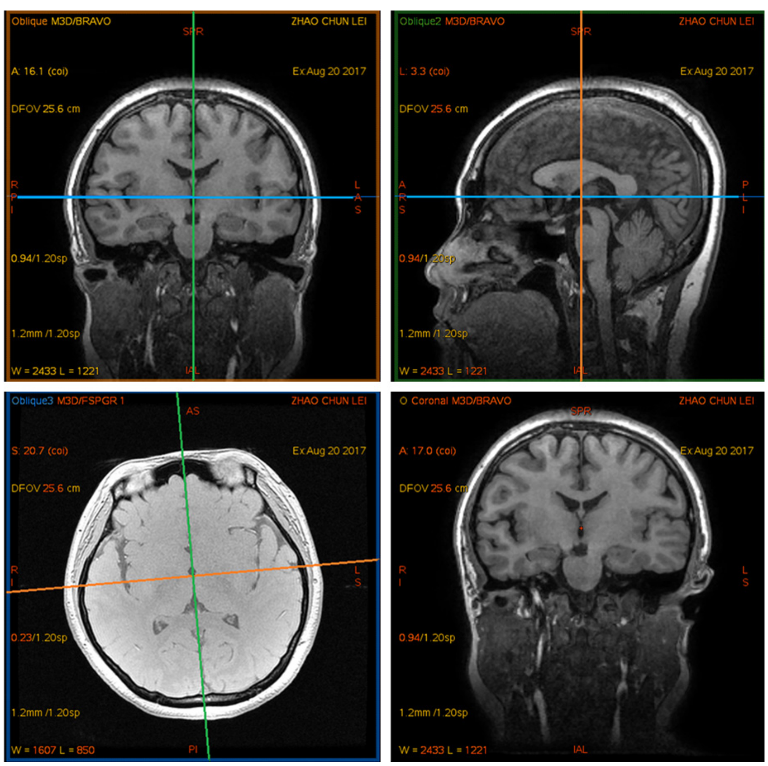

Figure 8. The top-left window selected (Step 3), the frontal plane (orange line) has been transferred to the black bone sequence.

the contour symmetry of the ROI, and display the soft and hard tissue details of the ROI (**Figures 12-15**).

Discussion

In this study, we describe a new method of analyzing craniofacial tissue symmetry in 3D using MRI black bone and soft tissue sequence data within a coordinate system, with the anterior cerebral falx represented as the median sagittal plane. The cerebral falx is the dura mater separating the cerebral hemispheres and can be used as a reference plane to evaluate craniofacial asymmetry.

There are a number of arguments in favor of using the cerebral falx as a reference plane. For instance, the forebrain, anterior cranial base, and mid upper facial midline are regulated by the same signaling factors. Thus, the 3 components are highly consistent in relation to each other [26]. The midline is a developmental axis of vertebrate embryos. This normally high consistency means that the forebrain, anterior cranial base, and mid-upper facial midline fully reflect both physiological and pathological conditions [22-25]. The prechordal plate defines the facial midline via signaling factors such as sonic hedgehog (SHH) and induces the forebrain to develop into two hemispheres, thus dividing the orbital area into two parts. The forebrain, anterior cranial base, and mid-upper facial midline are regulated by the same signaling molecules, thus the 3 are highly consistent [26].

The anterior cerebral falx divides the brain into mirror-image halves or hemispheres

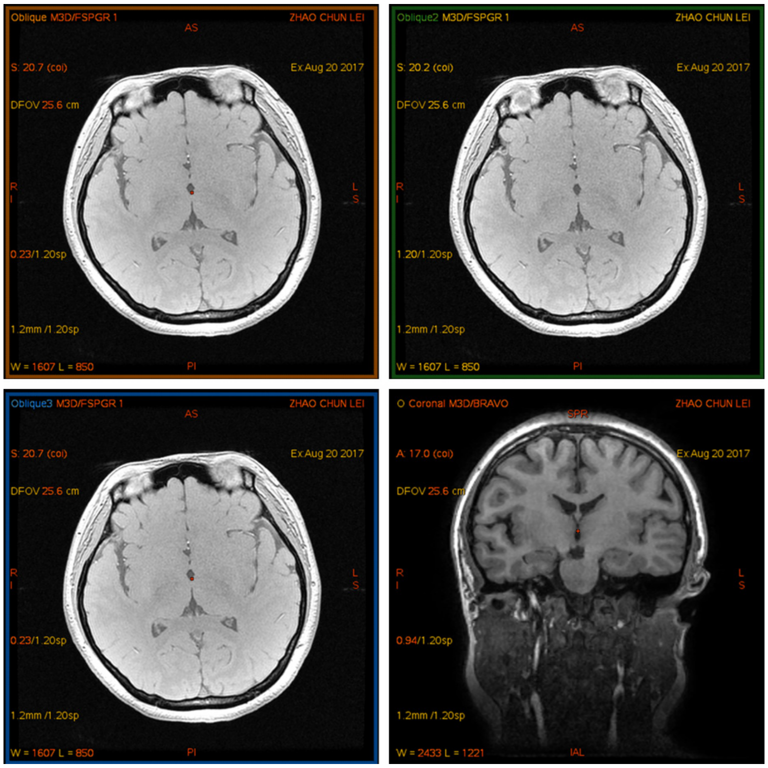

Figure 9. The top-right window and top-left window are changed to black bone sequences sequentially (Step 4).

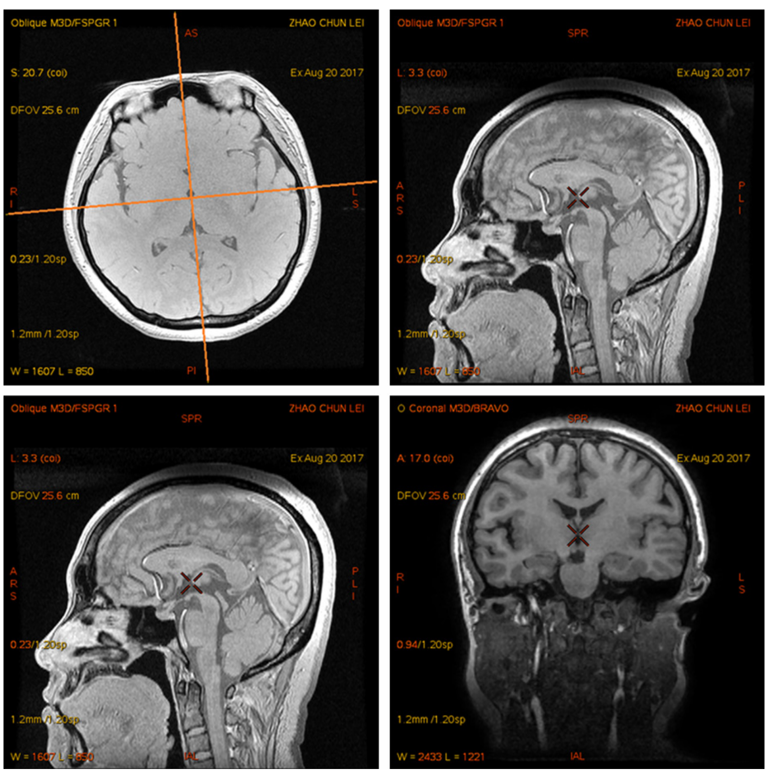

Figure 10. The oblique key selected, the 3D coordinate system is converted into a 2D coordinate system (Step 5).

and can be considered a sensitive and stable reference plane for evaluation of craniofacial asymmetry. It can replace the average distance between the inner tables of the skull as the gold standard midline reference plane during CT assessment of brain midline shift [35]. In contrast, the cerebral falx adjacent to the occiput (posterior) has a different embryonic origin [36] and may deviate from the midline [37]. Therefore, to avoid any bias, we used the cerebral falx anterior to the hypophyseal foramen as the median sagittal reference plane to evaluate craniofacial asymmetry. The upper face is considered a single module of nerves, bones, and muscles. Therefore, it has the best symmetry [38, 39].

Numerous researchers have demonstrated that asymmetry gradually aggravates from the upper to the lower face [40, 41]. This can be explained by the modular organization of the human cranium. Most functional and inherent craniofacial asymmetry is derived from the lower jaw-posterior cranium skeleton module. The anterior cranial base and mid-upper facial module are relatively stable, especially the upper third of the face. This further confirms the conclusions of human head anatomical network analysis, that the upper face is a single module of nerves, bones, and muscles and has the best symmetry [38, 39]. Thus, the cerebral falx, being located in the upper face, is likely to remain stable in patients with craniofacial asymmetry.

There are a number of advantages for using MRI, including

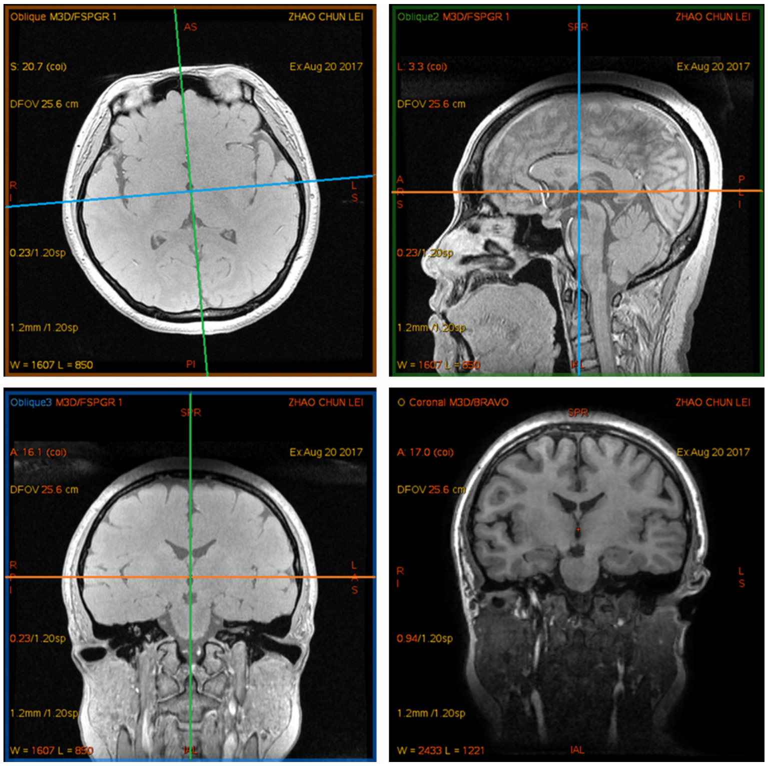

Figure 11. The top-left window is selected (Step 6), the 2D coordinate system is restored to a 3D coordinate system.

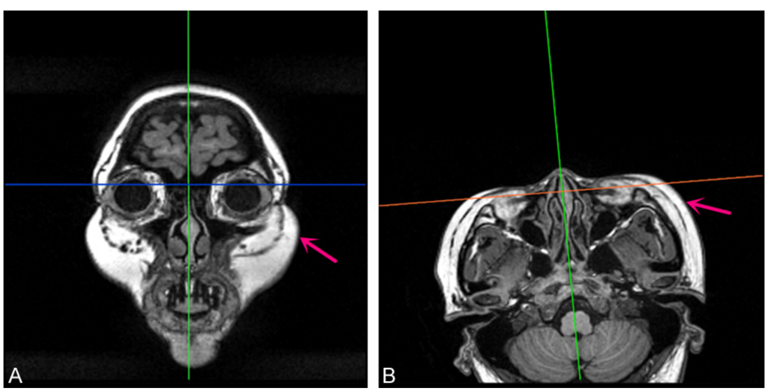

Figure 12. Example of craniofacial contour symmetry in the ROIs. Contour symmetry in the cheek region in the soft tissue sequence (arrow). A. Coronal symmetry. B. Horizontal and sagittal symmetry. The contour symmetry in the ROIs relative to the cerebral falx plane can be easily identified and measured.

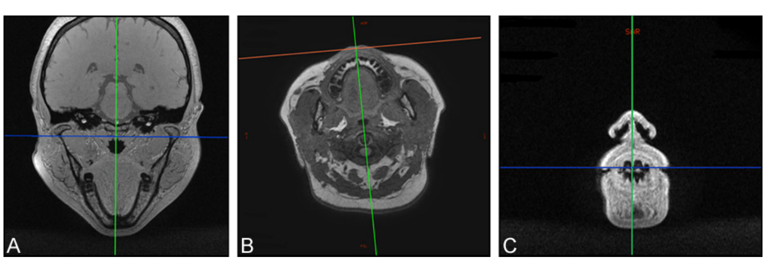

Figure 13. Example of relationship between cerebral falx plane and anatomical landmarks on the craniofacial midline. A. The distance between cerebral falx plane and mandibular symphysis in the black bone sequence. B. The relationship between the cerebral falx plane and philtrum, upper incisor contact in soft tissue sequence. C. The relationship between the cerebral falx plane and the nasal columella and upper and lower incisors in the soft tissue sequence. The relationship between the cerebral falx plane and soft and hard tissue anatomical landmarks on the craniofacial midline can be easily measured and defined.

prevention of radiation exposure and the ability to analyze craniofacial asymmetry in 3D based on the integrated and modular organization of the cranium. The boundary between the cerebra falx and brain parenchyma is clearly delineated, so it is convenient to position the cerebra falx in the MRI soft tissue sequence. On the other hand, muscles and other soft tissues are important in the occurrence and development of craniofacial asymmetry. Hence, the functional role of muscle and soft tissues cannot be ignored during the diagnosis and treatment planning of craniofacial asymmetry [42, 43]. In this situation, another advantage of MRI is its ability to evaluate soft tissues.

Volk and colleagues [44] analyzed quantitatively the MRI data of facial muscle volumes after 3D reconstruction to mimic muscles, and additionally for chewing muscles as controls innervated by the motor component of the trigeminal nerve. They reported that MRI is also valuable for analyzing muscles in patients with cra-

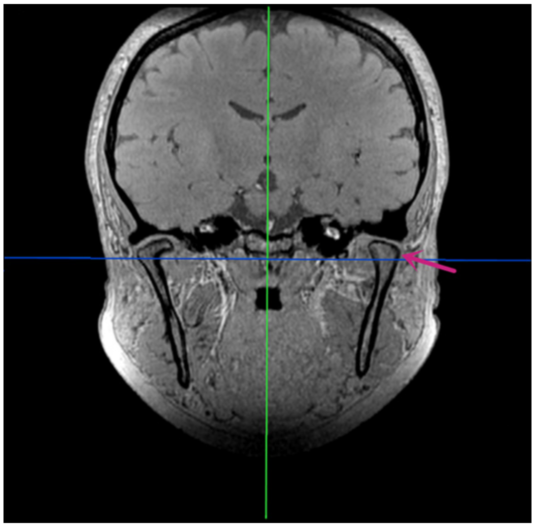

Figure 14. A clear display of the symmetry of the ROI condyle in a black bone sequence (arrow). By changing the position of the origin and the horizontal plane, with the cerebral falx as the median sagittal plane, the hard tissue symmetry of the ROI can be easily determined.

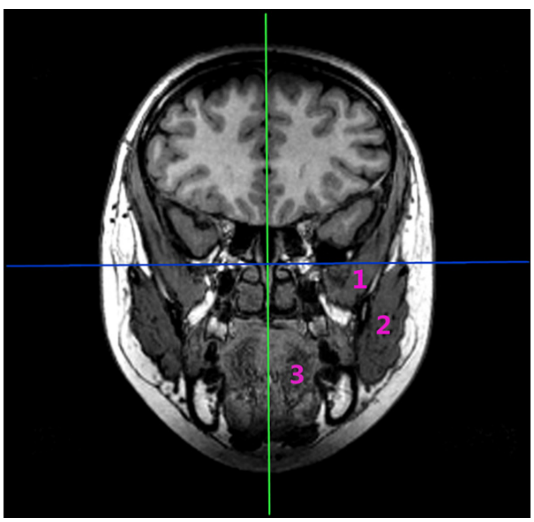

Figure 15. A representative MRI soft tissue sequence image showing the symmetry of muscles. Soft tissue symmetry of the ROI can be easily determined. 1, Temporalis muscle; 2, masseter muscle; 3, tongue.

niofacial asymmetry. We have noted that when using CT to locate the cerebra falx plane, although we identified the cerebra falx, the boundaries between the cerebra falx and brain parenchyma were not as clearly delineated as in MRI. Therefore, MRI has advantages over CT when using the cerebra falx as the median sagittal reference plane to ev-aluate craniofacial asymmetry.

The harm of ionizing radiation to the human body is well known [45, 46]. The cumulative effect of ionizing radiation is a significant concern, particularly in young patients with benign conditions. The majority of orthodontic and orthognathic patients are young, so minimizing or eliminating radiation exposure in diagnostic imaging is very important. MRI offers a non-ionizing method of imaging for patients. Therefore, it is possible to establish reference values in a database of 3D cephalograms obtained by MRI.

Although herein we propose a method to study the symmetry of craniofacial soft and hard tissues, it is a feasibility study only. The establishment of 3D measurements, development of a database, and reconstruction of skeletal and muscle tissues needs further research. As the proposed method requires 2 sequence scans for each patient, the cost is higher and requires more time.

In conclusion, this new method of obtaining MRI data via black bone and soft tissue sequences can be utilized with reference to a coordinate system. This coordinate system is constructed based on the integrated and modular organization of the human head, using the anterior cerebral falx plane as the median sagittal reference plane. This coordinate system can be transferred between soft tissue and black bone sequences to provide an accurate analysis of craniofacial contour and details of soft and hard tissue symmetry in 3D. In addition, preventing patients from exposure to unnecessary radiation, as in CT or CBCT, is an excellent benefit of using the proposed approach.

Acknowledgements

The experimental protocol was established, according to the ethical guidelines of the Helsinki Declaration and was approved by the Human Ethics Committee of Department of Image, Tongliao City Hospital, Tongliao 028000, Inner Mongolia, China. Written informed consent was obtained from individual participants.

Disclosure of conflict of interest

None.

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