An Evaluation of Handheld Ultrasonography Compared to MRI for the Diagnosis of Temporomandibular Joint Internal Derangement

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ABSTRACT

MRI is the gold standard of imaging modalities for the diagnoses of internal derangement (ID) of the Temporomandibular Joint (TMJ). MRI scans are non-invasive, use non-ionizing radiation, and provide valuable information on the position and morphology of joints, tissues and bony structures. MRI has disadvantages and patients with severe TMJ pain may find it difficult to complete a full TMJ scan series. The heavy demand for MRI utilization and resulting wait times prolong the interval between initial consultation and diagnosis. MRI is also expensive, inconvenient, and contraindicated in patients with certain metallic implants (Orhan & Aksoy, 2019). For these reasons, the author believes that finding an alternative diagnostic device for ID that is convenient and reliable is of critical importance.

There is a limited body of encouraging evidence demonstrating that mobile ultrasound sonography (mUS), can act as a diagnostic adjunct to MRI for assessment of Temporomandibular Joint Disorders (TMD’s), including ID and Degenerative Joint Disease (DJD). The use of mUS has no known contraindications, is readily accessible, comparatively inexpensive, and requires no special preparation (Orhan & Aksoy, 2019).

The purpose of this paper is to summarize the findings of original research into the Accuracy of handheld ultrasound sonography (HHU), in comparison to MRI, for the diagnoses of patients with TMD. The scans focussed on Anterior Disk Displacement (ADD) without reduction (ADDwoR), ADD with reduction (ADDwR) and arthritic changes (OA). Using a 95% CI and 5% p-value, when diagnosing ADDwoR, HHU was found to have a Sensitivity of 96.77%, Specificity of 100%, PPV of 100%, and NPV of 90%. When diagnosing ADDwR, Sensitivity was 76.50%, Specificity 100%, PPV 100%, and NPV 85.20%. The perfect Specificity means HHU is good at identifying patients that have a normal disc-condyle relationship and do not have ADD, while the perfect PPV means a high likelihood the tested patient has ADD.

Results indicate that HHU is a highly Specific test, with no false negatives, and an acceptable Sensitive test, with few false positives. HHU, in conjunction with questionnaires and clinical examination, shows promise as a first line imaging modality and screen for MRI referral.

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CONFLICT OF INTEREST

The author declares there is no conflict of interest in this article or study and that all ethical guidelines have been adhered to.

TABLE OF CONTENTS **Page**

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

ADD	Anterior disc displacement
ADDwoR	Anterior disc displacement without reduction
ADDwR	Anterior disc displacement with reduction
AUC	Area Under Curve
CBCT	Cone Beam Computed Tomography
CT	Computed Tomography
DJD	Degenerative Joint Disease
FP	False Positive
HHU	Handheld Ultrasound Sonography
ID	Internal Derangement
DJD	Degenerative Joint Disease
JIA	Juvenile Idiopathic Arthritis
MIP	Maximal Intercuspal Position
MRI	Magnetic Resonance Imaging
MSK	Musculoskeletal
mUS	Mobile Ultrasound
NLR	Negative Likelihood Ratio
NPV	Negative Predictive Value

PLR	Positive Likelihood Ratio
PPV	Positive Predictive Value
P-value	Probability Value
ROC	Receiver Operating Characteristic
TMD	Temporomandibular Joint Disorder
TMJ	Temporomandibular Joint
TP	True Positive
US	Ultrasound Sonography

CHAPTER 1

1.0 INTRODUCTION

1.1 Overview

MRI, Computed Tomography (CT), and Cone Beam Computed Tomography (CBCT), are the current diagnostic imaging standards for issues involving the TMJ. The advantages of these modalities include high-quality and detailed images and non-invasiveness.

MRI remains the gold standard and has the benefit of excellent soft tissue detail with no ionizing radiation. MRI is not without challenges, as patients with severe TMJ pain face long wait times and limited locations and may not be able to complete a full TMJ series. In addition, MRI is contraindicated in patients with metallic implants, coronary and peripheral artery stents, cardiac pacemakers, prosthetic heart valves, intrauterine contraceptive devices, and claustrophobia (Orhan & Aksoy, 2019). If an alternative to MRI could be found that was less expensive yet convenient, non-ionizing, and highly accurate, the burden on patient and health care system alike could be greatly reduced.

1.2 Mobile Ultrasound Sonography

There is a limited body of evidence demonstrating that mobile ultrasound sonography (mUS), can act as an adjunct or replacement to MRI as a diagnostic tool for TMD's, including ID and DJD, such as arthroses of the joint and joint effusions. The use of US has no known contraindications, is readily accessible, comparatively inexpensive, and requires no special preparation (Orhan & Aksoy, 2019).

Friedman et al. found US had a Sensitivity of 79%, and a Specificity of 100%, when comparing mUS scans to MRI for scans of ID (Friedman et al., 2020). A similar study by Talmaceanu et al., found a Sensitivity of 72.58%, and Specificity of 86.84%, when comparing US scans at 13MHz to MRI for scans of ID (Talmaceanu et al., 2020).

1.3 Purpose

The purpose of this paper is to determine if HHU, as suggested by mUS results, is a credible alternative or adjunct to MRI, for the most common intraarticular joint disorders. The null hypothesis was that HHU would not have sufficient Accuracy, in comparison to MRI, to act as a diagnostic modality for TMDs. The cut-off for statistical significance was a 5% p-value, at a 95% CI, and the resulting p-values were $\leq .001$ for HHU scans of ADDwoR and ADDwR and thus the null hypothesis was rejected. HHU scans for OA did not meet the required p-value for statistical significance and the null hypothesis for the diagnoses of OA is not rejected.

CHAPTER 2

2.0 HYPOTHESIS AND OBJECTIVES

2.1 Hypothesis

The null hypothesis was that HHU was not an accurate diagnostic modality for the identification of disease or non-disease in patients with TMD symptoms. The alternative hypothesis was that HHU was as statistically accurate a diagnostic modality as MRI, for the identification of disease or non-disease in patients with TMD symptoms.

Hypothesis:

H_0	Null: HHU is not statistically accurate in predicting ID in patients when compared to the standard of MRI (i.e., there is no significant statistical correlation between diagnostic modalities).
H_a	Alternative: HHU is statistically accurate and can predict ID in patients when compared to the standard of MRI (i.e., there is a significant statistical correlation between modalities using an alpha (α) of $\leq 5\%$ to reject the null hypothesis (H_0)).

2.2 Objectives

The study seeks to determine the efficacy of HHU in relation to MRI for the diagnoses of ID and DJD in patients complaining of TMD symptoms. The study seeks to evaluate, with statistical analysis, whether HHU is sufficiently accurate in clinical practise to replace or supplement MRI for the diagnosis of common TMD's. If HHU is confirmed to be as accurate as MRI, there could be significant improvements in the rapid identification and treatment of TMD's and thus improve outcomes for patients while reducing the demand for MRI services and the burden on the health care system.

CHAPTER 3

3.0 MATERIALS AND METHODS

3.1 Approval

The study design, research protocol, and ethical considerations, were reviewed and approval by the Research Ethics Board (REB) of the Winnipeg Regional Health Authority (approval no. B2022:010 (HS25365)) prior to commencement. The study was also registered as an active and approved Clinical Trial on ClinicalTrials.gov. Patients were screened and recruited at the Department of Oral and Maxillofacial Surgery at the Health Sciences Centre in Winnipeg, Manitoba. Informed consent was obtained from each patient by a member of the Oral and Maxillofacial Surgery team.

3.2 Privacy

Each of the patients' MRI's and US scans were assigned a randomly generated number and all other patient identifiers were removed. The unique number assigned to each patient was documented in a Master Key. Patient details were encrypted and kept confidential in accordance with the regulations of the REB and Manitoba Freedom of Information and Protection of Privacy Act. All documentation complies with the College of Physicians and Surgeons of Manitoba by-laws, statements, and guidelines, for electronic medical records (including consultation requests). The rights and interests of indigenous individuals were acknowledged and their participation included in this study.

3.3 Magnetic Resonance Imaging

MRI uses radio-frequency pulses to accurately and noninvasively image hard and soft tissues. An MRI machine is composed of four major components: the superconducting magnet, gradient system, radio-frequency transmitter and receiver, and the computer system (Rozylo-Kalinowska & Orhan, 2019). Superconducting magnets generate a strong external magnetic field which realign the body's atoms. The gradient system produces alternative magnetic fields in the x, y and z axes. The radio-frequency transmitter and receiver allow for signal acquisition following slice selection and gradient application, which is then interpreted by the computer system (Rozylo-Kalinowska & Orhan, 2019).

MRIs are based on the concept that all materials are composed of protons, neutrons and electrons, and protons and neutrons revolve around their own orbits, generating their own magnetism. When an external magnetic field is applied to the body, protons align with or against the field. When enough magnetic force is applied, such as when an MRI is performed, the ratio of protons aligned with the magnetic field increases (Rozylo-Kalinowska & Orhan, 2019) **(Figure 3.3.1).**

Following excitation by radiofrequency, the atoms then return back to their base state by one of two processes: T1 or T2 relaxation. In T1 relaxation, or spin-lattice interaction, energy is transferred from the atoms to the neighboring molecules of surrounding tissues in the z-direction and the atoms eventually realign with the external magnetic field. As the molecular structures vary between tissues, the T1 relaxation time varies as well. Acquisition of images is also dependent on both Repetition time (TR) and Echo time (TE). TR refers to the time between RF pulses applied to the tissues. TE refers to the time between RF pulses and the MR signal sampling. Typically, T1-weighted images have shorter TE and TR times, although TR is the main determinant of T1 imaging. For example, fat atoms quickly realign themselves between pulses, and therefore have a short T1 relaxation time, appearing bright on MRI. Alternatively, cerebrospinal fluid produces a weaker MR signal because it takes a long time to regain longitudinal magnetization and appears dark on MRI (Rozylo-Kalinowska & Orhan, 2019) **(Figure 3.3.2).**

In T2 relaxation, or spin-spin interaction, the rate of decay of the magnetization is detected in the z-y plane. The emission of energy from the decay creates an electric voltage which is detected by a receiver. In addition, T2-weighted images have longer TE and TR times although TE is the main determinant of T2 imaging. For example, fluid-rich tissues such as those with infection, edema, inflammation and CSF have a short T2 relaxation time as the atoms are able to reach equilibrium with one another quickly, appearing bright on MRI (Rozylo-Kalinowska & Orhan, 2019).

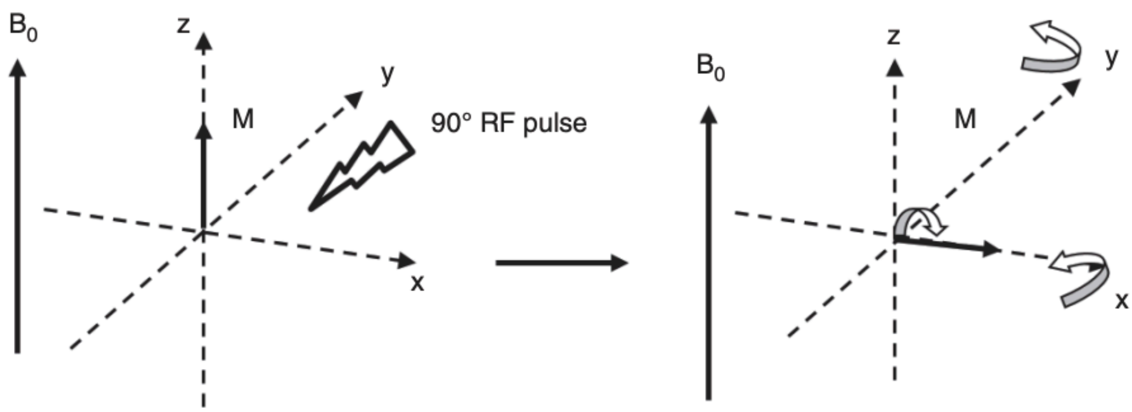

Figure 3.3.1. Magnetic Rotation. In the presence of a magnetic field, net longitudinal magnetization occurs in the z axis, and after a 90-degree RF pulse application, longitudinal magnetization tips down and rotate into transverse magnetization (Rozylo-Kalinowska & Orhan, 2019).

3.3.1 Advantages

MRI is currently the gold standard of imaging modalities for the TMJ and associated structures, as it provides valuable soft tissue visualization in sagittal, axial and coronal views. MRI allows for excellent visualization of the articular disc, which typically appears with low signal intensity on the T1-weighted images. The articular eminence and condylar head can be easily identified as they are brighter on T1-weighted images due to the presence of yellow marrow. Alternatively, edema and inflammation are best evaluated with T2, and appears bright due to increased signal intensity. The bone marrow of the condylar head and articular eminence can also appear brighter on T2-weighted images due to marrow edema secondary to inflammation. Sclerosis of the condylar head presents with decreased signal intensity on both T1 and T2-weighted images due to increased density and decreased yellow marrow (Rozylo-Kalinowska & Orhan, 2019) **(Figure 3.3.1.1).** Often, pseudo-dynamic imaging is obtained of the TMJ by acquiring MRIs in both closed mouth and open mouth positions of various degrees. These images are then strung together to provide a simulation of condylar movement for the clinician **(**Rozylo-Kalinowska & Orhan, 2019) (**Figure 3.3.1.2)**).

3.3.2 Disadvantages

Artifacts on MRI are relatively common and a difficult problem to overcome. Patient motion is a common cause of artifact as MRI acquisition takes longer than other forms of imaging, resulting in artifacts becoming more obvious and making it more difficult for some patients to remain still. Even involuntary movements such as swallowing, respiration and cardiac motion can cause artifacts. Another common cause is metal, such as surgical metals and implants, dental restorations and orthodontic appliances. Metals have their own magnetic fields, and interfere with the RF applied by MRI, severely reducing the image quality of adjacent structures (Rozylo-Kalinowska & Orhan, 2019). MRI has many contraindications to its use, including metallic implants or clips, coronary or peripheral artery stents, prosthetic heart valves and inferior vena cava filters pose a risk if the material they are fabricated from is ferromagnetic. Foreign bodies can also cause damage to vessels and nerves if the magnet causes it to

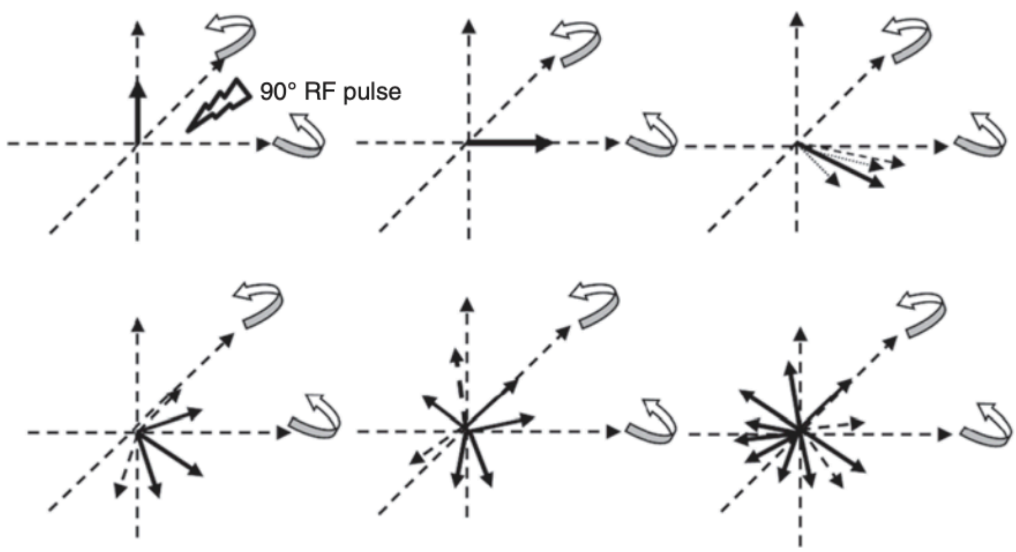

Figure 3.3.2 Transverse magnetisation. Transverse magnetization is at maximum while the protons are in phase, due to the inter- and intramolecular interactions, protons begin to process at different frequencies (Rozylo-Kalinowska & Orhan, 2019)

shift within the tissues. Pacemakers have the potential to become affected by the magnets or RF, leading to inadequate asynchronous pacing or tachyarrhythmias, although most modern pacemakers have a programmable magnet function. Depending on their material, implanted contraceptives and cochlear implants can also shift as a result of the MRI. Other potential contraindications include tattoos and cosmetics, which contain metal particles that can heat up during MRI leading to pain and irritation. Claustrophobia poses another challenge, as MRI acquisition is more time consuming, restrictive and deafening than other imaging modalities. Sedation may be required in these patients depending on the severity (Rozylo-Kalinowska & Orhan, 2019).

3.4 Ultrasound Sonography

Ultrasonic sonography (US) devices are appropriately named as they emit sound waves in frequencies above the range of human hearing. US transducer pulses are created from piezoelectric crystals within the machine, which forms vibrational energy that travels through tissues. The densities of the tissue determines "acoustic impedance", which is the frequency-dependent resistance that the beam encounters as it travels. The larger the difference in acoustic impedance between tissues, the greater the directed reflection of the ultrasonic wave back to the piezoelectric crystals, also known as echoes (Fig v, Li et al., 2021). Deformation of these crystals creates an electrical current which is transmitted to a computer system to form an image (Li & Ming-Der Chow & Vadivelu & Kaye, 2021). Structures that are denser, such as bone, produce strong echoes and are known as hyperechoic, whereas structures that have lower echogenicity such as fluid are known as hypoechoic (Rozylo-Kalinowska & Orhan, 2019).

US is classified based on the frequency of sound waves that they emit. Frequency is the number of cycles per second that the US emits. Frequency is inversely proportional to wavelength, which is the distance between two points on a wave in a cycle, and the higher the frequency, the shorter the wavelength. As shorter wavelengths do not penetrate tissues as readily, higher frequency settings are normally reserved for imaging more superficial structures (Li et al., 2021). The Butterfly iQ ultrasound

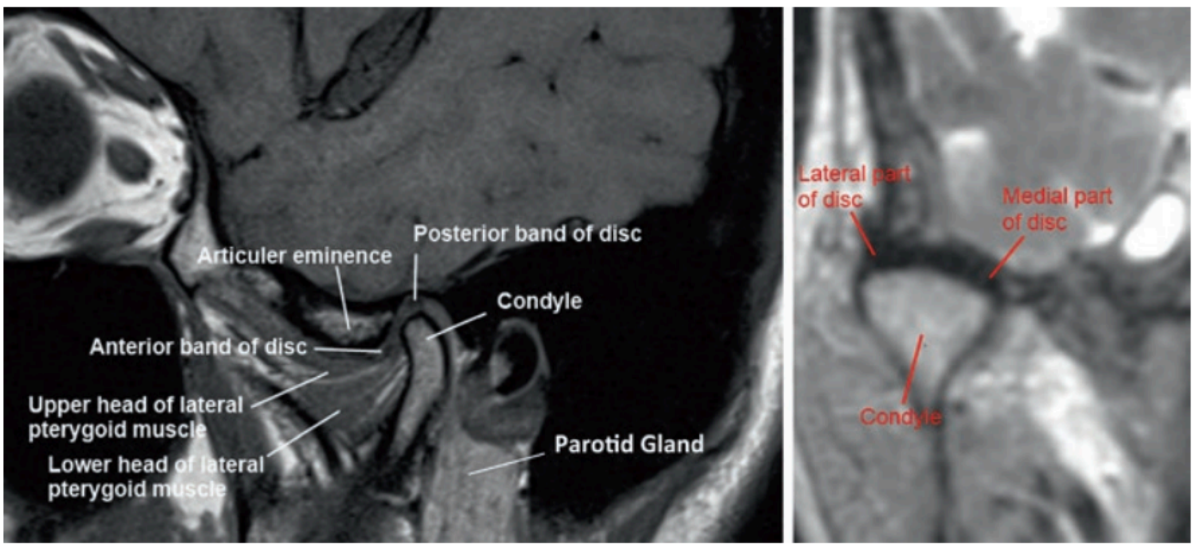

Figure 3.3.1.1. MRI image of diseased TMJ. Sagittal and coronal MR images showing the anatomical landmarks of TMJ (Rozylo-Kalinowska & Orhan, 2019)

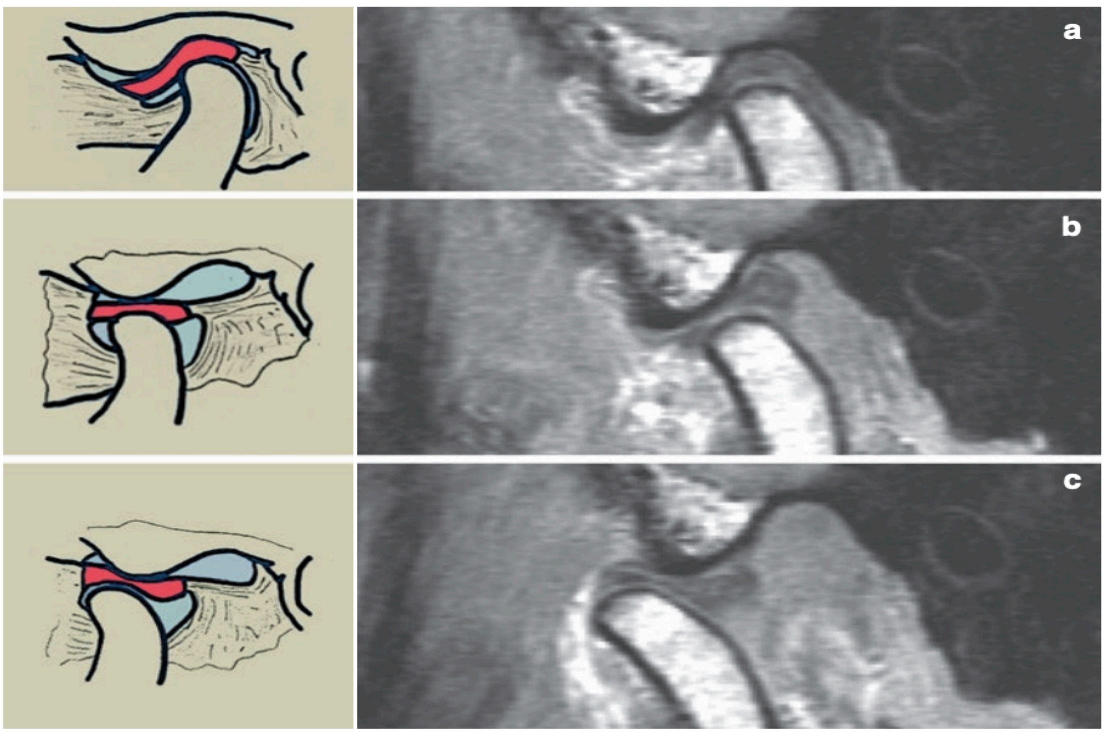

Figure 3.3.1.2 MRI of a normal joint. MRI of a normal joint: a) closed, b) partially open, and c) open mouth positions (Rozylo-Kalinowska & Orhan, 2019).

ranges from 1-10 MHz, and the average depth of the TMJ is less than 2cm, far less than many bodily structures, making it an excellent candidate for US imaging **(Appendix B).**

3.4.1 Advantages

The advantages of US are numerous, and include cost effectiveness, availability in most health care centres, real-time imaging, quick administration, and high-quality image resolution. One of the greatest advantages is that there are no known contraindications, and even the most medically complex or unstable patients are able to safely undergo US studies.

3.4.2 Disadvantages

The disadvantages of US include a lack of image acquisition in axial, coronal and sagittal views, and structures located medial to bony are obscured. US images the lateral aspect of the TMJ; the lateral condyle, articular eminence, disc and musculature and can omit information not present in this view. In addition, US is highly dependent on operator skill and requires training for proper acquisition and interpretation (Li et al., 2021).

3.5 Temporomandibular Anatomy

The TMJ is a derivative of the first pharyngeal arch and develops inside Merkel's cartilage. It is a biconcave, synovial and diarthrodial joint. The articular disc, a biconcave structure made of fibrocartilage, separates the joint space into superior and inferior compartments. The superior compartment is bounded by the articular fossa of the temporal bone and allows for translational movement, while the inferior compartment is bounded by the mandibular condylar head and allows for rotational movement **(**Slusarenko & Borba & Naclério-Homem, 2020) (**Figure 3.5.1.)**. The vascular supply to the TMJ comes from branches of the superficial temporal, deep auricular, anterior tympanic and ascending pharyngeal arteries. These arteries, along with the pterygoid plexus, supply and drain the disc periphery and posterior joint region, respectively. The TMJ capsule, disc periphery and retrodiscal tissue are supplied by the auriculotemporal, masseteric and deep temporal nerves (Bhargava, 2021).

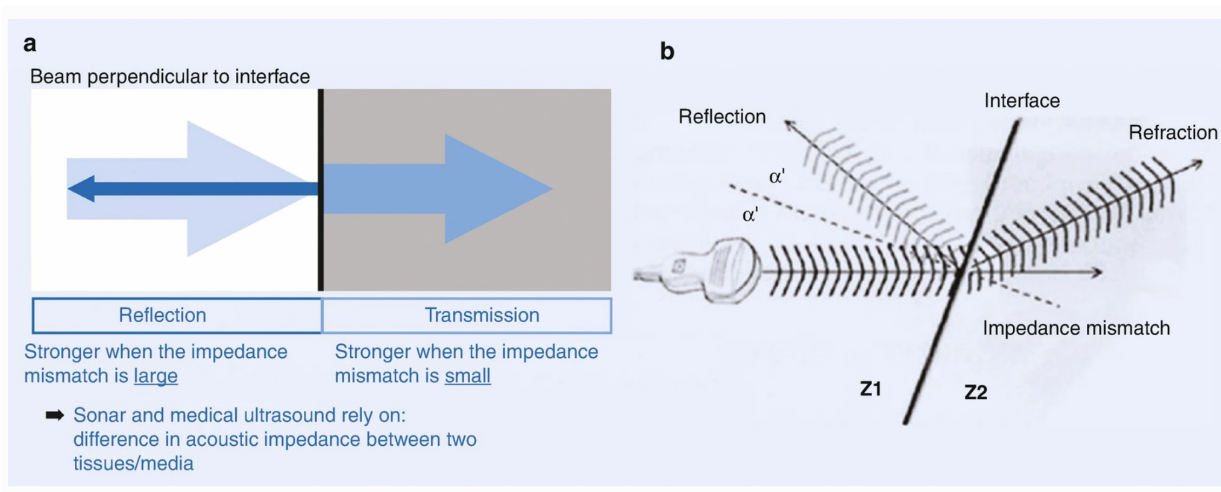

Figure 3.4.1 Ultrasound Image. v. a) Generation of an ultrasound image: reflection versus transmission. b) Interaction of ultrasound with interfaces in the body according to the laws of wave optics (Li et al., 2021)

3.5.1 Articular Disc

The disc itself is divided into three portions: the posterior band, intermediate zone and anterior band. The anterior and posterior bands are both composed of superior and inferior lamellae. The superior lamellae of the anterior band attaches to the articular eminence, while the inferior lamellae attaches to the condylar head. The superior lamellae of the posterior band attach to the squamotympanic fissure, while the inferior lamellae fuses with the periosteum of the condylar neck. The posterior aspect of the disc is connected to the highly vascular and innervated retrodiscal tissue, which is important for protecting the joint from extreme rotational and translatory movements. In part, it is often articulation on this tissue that causes pain and discomfort for patients with ADD due to its rich neural supply (Bhargava, 2021).

The TMJ is unique as a ginglymoarthrodial joint, meaning that it has both rotational and translatory motions depending on the degree of opening. Translation occurs in the superior compartment while rotation occurs in the inferior compartment. During normal function, the articular disc is positioned between the fossa and articular eminence and is kept in place by the action of the superior lateral pterygoid and retrodiscal tissue. Upon opening, contraction of the inferior lateral pterygoid protrudes the mandible, allowing the condyle to rotate and translate. Stabilization of the disc during opening is also controlled by the superior and posterior retrodiscal lamina which pulls the disc posteriorly to maintain its position during anterior translation of the condyle. During closing, the superior lateral pterygoid muscle contacts to stabilize the disc against the posterior slope of the articular eminence, maintaining its position during posterior translation of the condyle (Bhargava, 2021).

3.6 Temporomandibular Disorders

3.6.1 Prevalence

TMD’s are common, with reported prevalence of up to 75% reported in the literature. This condition affects people of all ages; however, the peak age range is in the second to fourth decades of

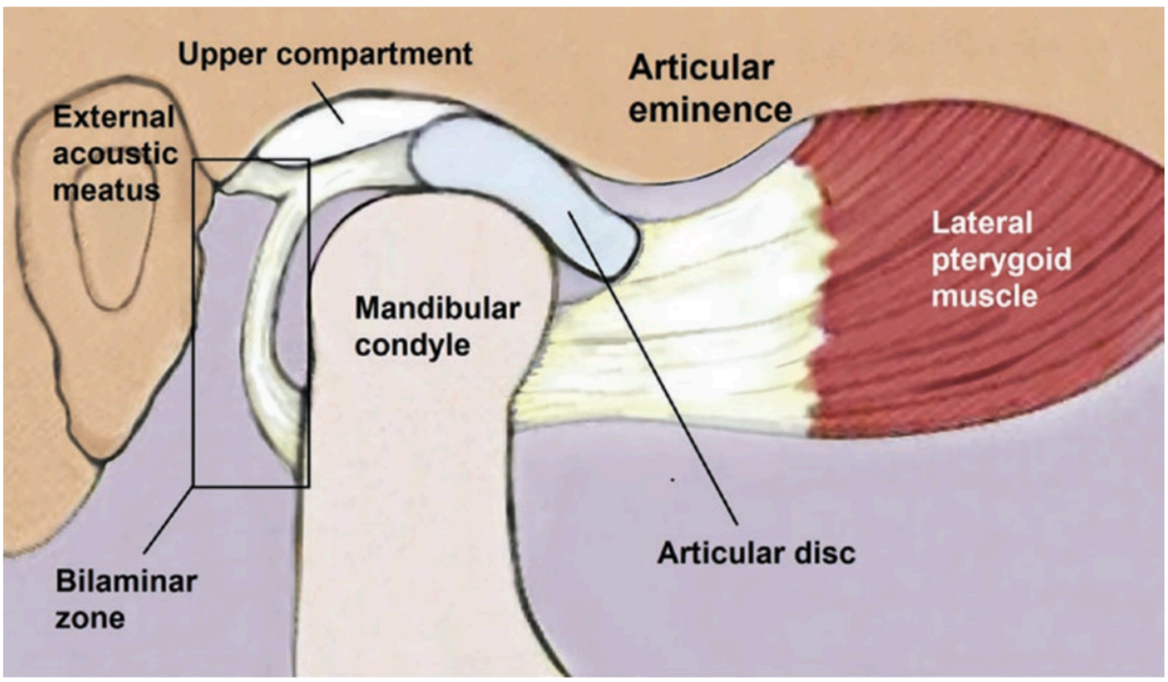

Figure 3.5.1. Anatomy of the TMJ with the jaw closed. (Slusarenko & Borba & Naclério-Homem, 2020)

life with females affected more than males. One of the most common TMD's is internal derangement, a pathologic condition of the TMJ whereby the articular disc loses its normal relationship with the condylar head, broadly categorized into ADDwoR and ADDwR. Multiple studies of different populations, including those by Muthukrishnan et al. and de Paiva Bertoli et al., have demonstrated the incidence of internal derangement to be around 38% in Chennai and Brazilian populations, respectively (Muthukrishnan & Sekar, 2015; Bertoli et al., 2018). Due to their prevalence and associated disability, work-up, diagnosis and imaging of TMD's represent a significant burden to the health care system (Young, 2015) **(Table 3.6.1).**

Wilke's classification is a widely used classification system which describes the reduction of the articular disc (Young, 2015) **(Table 3.6.2.).** Based on the classification level, a patient's pain, symptoms, disc condition and joint anatomy can often be predicted (Young, 2015).

3.6.2 Anterior Disc Displacement without Reduction

ADDwoR occurs when the condyle is able to make rotational movements upon opening, but the condylar head is unable to articulate with the intermediate zone of the disc as it is physically blocked from translation by the disc itself. As the patient continues to open, the contralateral condylar head will continue to translate, leading to mandibular deviation to the affected side with a maximal incisal opening of less than 30mm (Okeson, 2019) (**Figure 3.6.2.1.).** The patient will often complain of an inability to open fully (Bhargava, 2021).

Similar to ADD with reduction, MRI reveals the posterior band of the disc anterior to the 11:30 position of the condylar head and the intermediate zone of the disc anterior to the articular eminence in MIP (Bhargava, 2021) (**Figure 3.6.2.2**). However, the intermediate zone of the disc remains anterior to the condyle even with maximal opening. Oftentimes, patients will seek treatment for this condition as it noticeably interferes with their daily function including eating and speaking. Treatment ranges from conservative to surgical, such as arthrocentesis, arthroscopy and open joint surgery depending on severity and patient discomfort (Bhargava, 2021).

When the retrodiscal tissues and collateral ligaments stretch, they can become abnormally lax, leading to anterior movement of the disc. Once the disc is positioned anteriorly, the retrodiscal tissue and ligaments become positioned where the disc previously sat, effectively transforming into a "pseudodisc". This pseudodisc is subjected to repeated loading during function of the joint, leading to adaptive changes including fibrosis of blood vessels and nerves. In some people, the pseudodisc can function well and allow for normal movement of the joint. In other cases, function on this retrodiscal tissue causes pain and discomfort for the patient as nociceptors within become activated (Gateno et al., 2004).

3.6.3 Anterior Disc Displacement with Reduction

ADDwR is diagnosed when the patient has a disc that is located anterior to the condylar head. As the patient's jaw opens, the condyle translates forward and articulates with the intermediate band of the disc. This can make an opening "click" sound, and is known as reduction of the disc. When the patient closes, the condyle translates backwards and articulates back onto the retrodiscal tissue. This movement can make a reciprocal "click" sound. Therefore, patients with ADD with reduction may complain of both opening and closing "clicks" (Okeson, 2019) (**Figure 3.6.3.1.).**

MRI examination can confirm this diagnosis with the following: in MIP, the posterior band is located anterior to the 11:30 position of the condylar head and the intermediate zone is anterior to the articular eminence; upon opening, the disc is reduced, and the intermediate band is between the condylar head and articular eminence (Bhargava, 2021). **(Figure 3.6.3.1)**

Typically, patients with ADDwR and an associated painless click can be counselled on conservative management, such as soft diet, NSAIDs, muscle relaxants, avoidance of sticky and chewy foods, and use of a brux guard. However, patients presenting with a painful clicking may require adjunctive treatment, including surgery (Bhargava, 2021).

Table 3.6.1 Incidence of common TMD's. Incidence of common TMD's reported by various authors in their study samples (Young, 2015).

Condition		Incidence
Deviation of the joint	17%	
Rheumatoid arthritis	10%	
Myofascial Pain Dysfunction Syndrone (MPDS)	1% - 10%	A study reported less than 0.8% prevalence in the South Indian population, and 10.3% in the Brazilian population.
Internal derangement	38%	A study reported 78% incidence in Japanese population.
Disc displacement	8%	
TMJ arthralgia	3% - 4%	
Osteoarthritis	14% - 15%	
TMJ tuberculosis	10%	Extra-pulmonary manifestations of TB.
TMJ ankylosis		Ankylosed joint has a higher prevalence in developing countries, and has a rising incidence in India. Among ankylosis cases, the post-traumatic ankylosis is most common (87%). The condition is more commonly reported in children.

Table 3.6.2 Staging of the disc disorders. Staging of the disc disorders based on Wilkes classification of internal derangements (Young, 2015).

Stage	Pain	Opening	Disc location	Anatomy
I	Occasional painless click	No limitation	Slightly forward	Normal
II	Painful click	Intermittent locking	Moderate anterior disc displacement	Disc deformity
III	Pain during function	Locked and restricted motion	Complete disc displacement	Disc deformity/no bony or early changes
IV	Continuous pain	Locked and restricted motion	Complete disc displacement	Moderate degenerative bony changes
V	Severe pain	Locked and severely	Perforation of retrodiscal tissue;	Severe degenerative bony changes

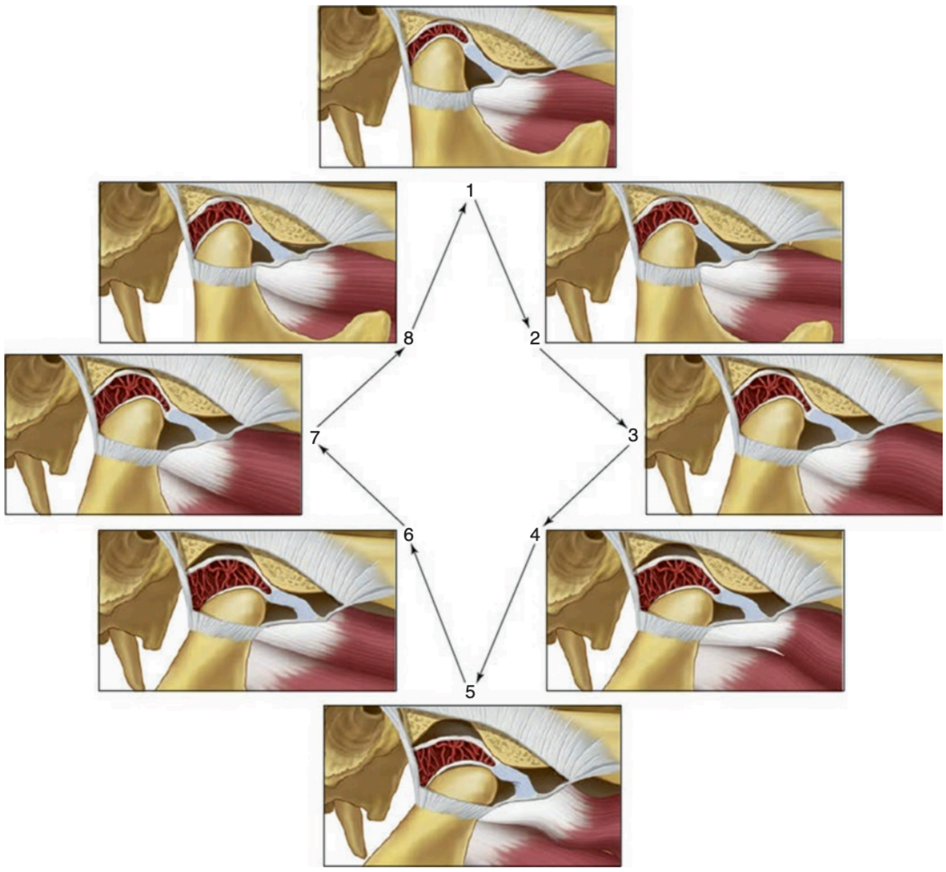

Figure 3.6.2.1. Disc Displacement Without Reduction. Note that the condyle never assumes a normal relationship on the disc but instead causes the disc to be maintained in front of the condyle. This condition limits the distance it can translate forward (Okeson, 2019)

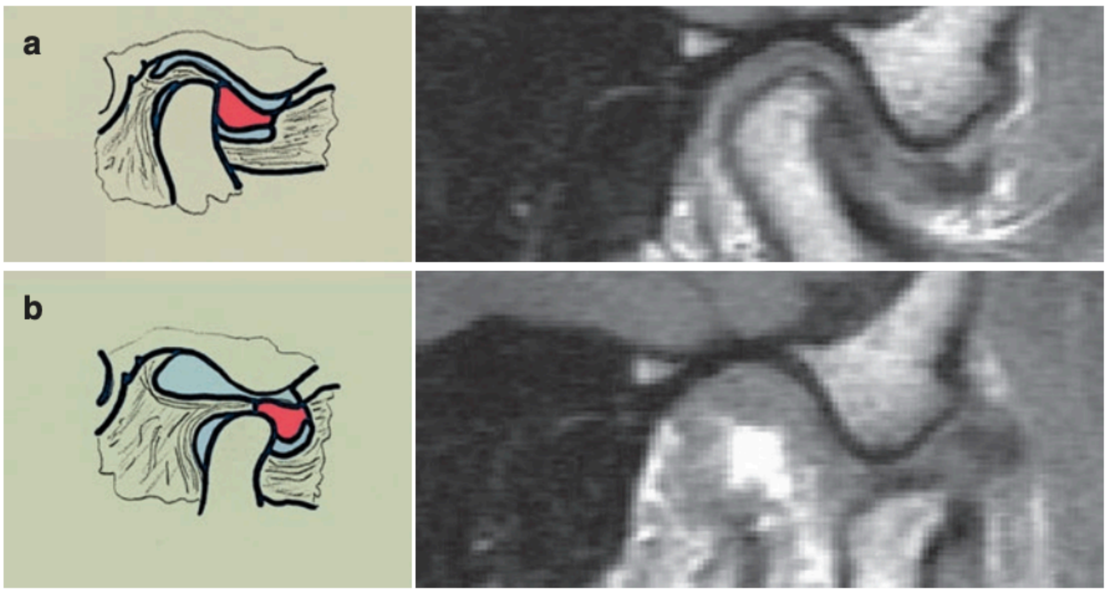

Figure 3.6.2.2 MRI of ADDwoR. MRI of ADDwoR: a) closed and b) open mouth positions (Bhargava, 2021)

3.6.4 Osteoarthritis

OA is another common cause of TMJ dysfunction and has many different etiologic factors. Often, a detailed history and physical examination is required to differentiate between causes as signs and symptoms present similarly across the board (Bhargava, 2021). OA can be broadly classified into either low inflammatory OA or high inflammatory arthritis, and low inflammatory arthritides include DJD such as OA. OA origins are either primary or secondary from trauma or hypermobility, and results when the articular cartilage deteriorates and becomes weakened from overloading. The bone of the condyle then resorbs and remodels, which can form osteophytes. Typically, OA is more common in females above 40 and is gradual in onset. Symptoms include joint pain which worsens with use, crepitus, swelling, decreased maximal incisal opening and pain on palpation. There are three main classifications of osteoarthritis, with class I representing early disease, class II representing arrested disease and class III representing advanced disease. Classification is important as treatment options vary between classifications. For class I disease, non or minimally invasive management is recommended.

For arrested disease, treatments aimed at treating the affected bone and joint are pursued. Finally, for class III advanced disease, salvage procedures to try and limit the progression of disease are recommended, although permanent damage to the joint has occurred at this stage (Bhargava, 2021). (**Table 3.6.3).** Imaging of patients with TMJ arthritis, using CT scans, MRI or plain films, demonstrates erosion of the condylar head, with anterior lipping and narrowing of the joint space. Oftentimes, osteophyte and subchondral cyst formation can also be seen (Bhargava, 2021).

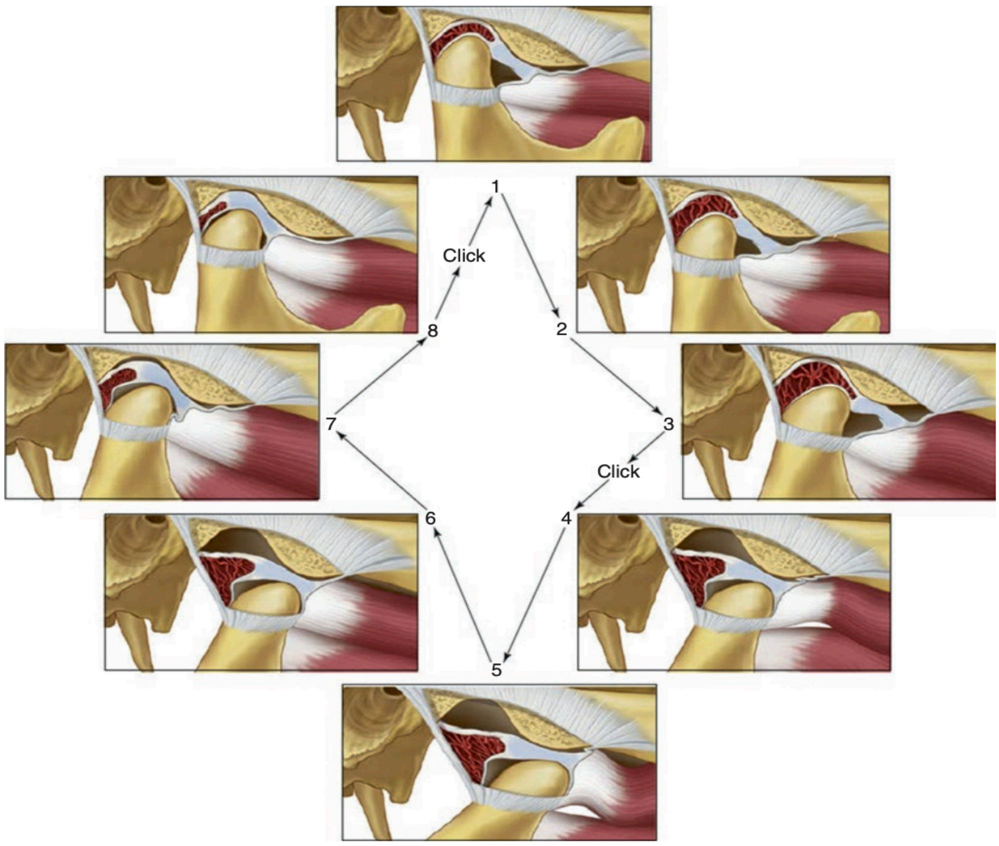

Figure 3.6.3.1. Disc displacement with reduction. Note that during opening, the condyle passes over the posterior border of the disc onto the intermediate area of the disc, thus reducing the anterior displaced disc. The discal movement can lead to momentary mechanical catching or locking. When this is present, the condition is called disc displacement with intermittent locking (Okeson, 2019).

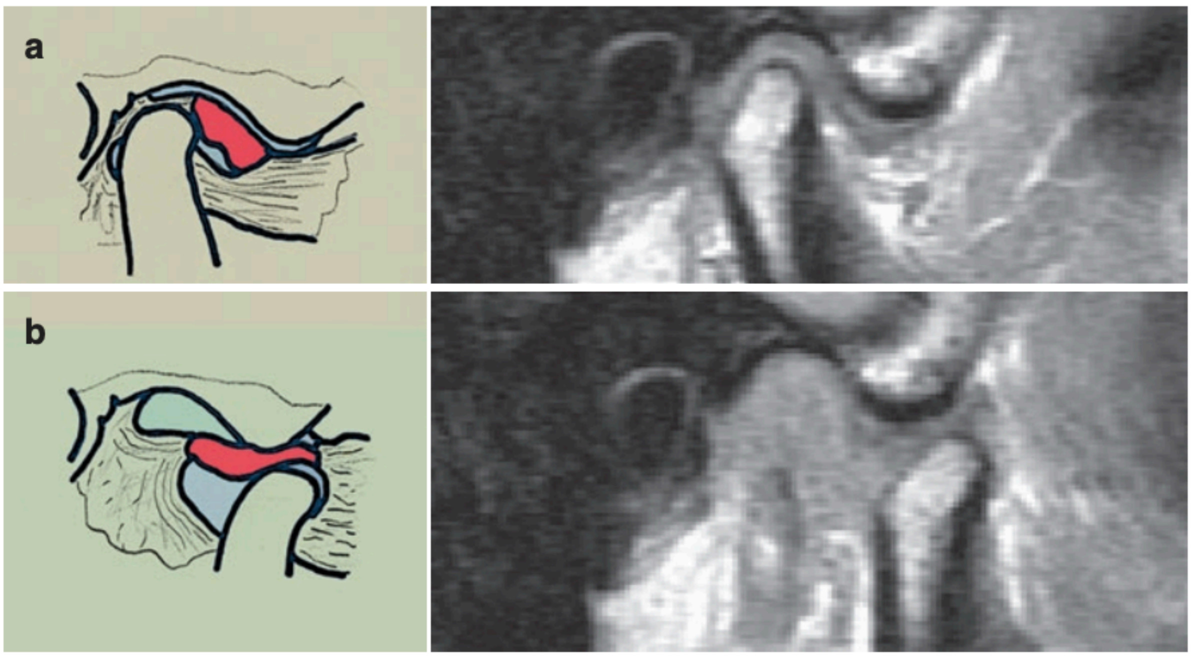

Figure 3.6.3.2 MRI of ADDwR. MRI of ADDwR: a) closed and b) open mouth positions (Bhargava, 2021)

High inflammatory OA includes diseases such as septic arthritis, metabolic arthritis, systemic arthritides associated with connective tissue disease, and inflammatory arthritides such as rheumatoid arthritis, psoriatic arthritis, juvenile idiopathic arthritis, Ankylosing Spondylitis and Reiter syndrome. Most radiographic findings of high inflammatory arthritides are nonspecific and vary widely depending on severity. Findings include loss of joint space, erosion of the condylar head, flattening of the articular eminence and possible subchondral cysts (Bhargava, 2021).

3.7 REVIEW OF THE LITERATURE

3.7.1 Ultrasound Sonography

There are several studies comparing high frequency sonography to MRI for diagnosing TMJ disc displacement. Friedman et al. (2020) obtained US images of the TMJ with a Philips 15-7 MHz L15-7io hockey stick transducer in open and closed mouth positions. They reported a Sensitivity of 79%, Specificity of 100%, PPV 100%, and NPV 84%, for mUS when compared to MRI. Their study showed that US was highly effective at correctly identifying patients without disease as negative (Friedman, 2020). However, they did find that medial displacement of the disc was not readily identified. Several other studies comparing US and MRI are in agreement with these findings. A study by Talmaceanu et al., found a sensitivity of 72.58%, and specificity of 86.84%, when using 13MHz mUS for overall disc displacements when compared to MRI (Talmaceanu et al., 2020). Kalyan et al. and Razek et al. also confirmed high specificity when comparing US with MRI. They combined their US findings with TMJ auscultation during clinical examination, which led to even greater diagnostic accuracy (Kalyan et al., 2017 & Razek et al., 2014).

3.7.2 Meta-Analysis

One of the most comprehensive studies on this topic is a systematic review and meta-analysis performed by Li et al. (2012), which analyzed 14 cohort studies and one case control study. Overall, they found that mUS had acceptable diagnostic accuracy compared to MRI. For ADDwoR, mUS had a

Table 3.6.3 Classification of Osteoarthritis (Bhargava, 2021)

Stage	Symptoms	Signs	Imaging	Management options
I Early disease	Joint/muscle pain Limited function Crepitus	Little or no occlusal or facial aesthetic changes	Mild to moderate erosive changes of condyle/fossa/eminence	Non-invasive (1°) Minimally invasive (2°)
II Arrested disease	Little or no joint pain Muscle pain Some joint dysfunction Crepitus	Class II malocclusion Apertognathia	Flattened condyle/eminence	Bone and joint (1°) Salvage (2°)
III Advanced disease	Joint/muscle pain Loss of function ± Crepitus Progressive retrognathia	High-angle class II malocclusion Apertognathia Developing fibrosis/ ankylosis	Gross erosive changes Loss of condyle and eminence height Ankylosis Hypertrophy of coronoid	Salvage (1°)

Sensitivity of 0.79, Specificity of 0.91, PLR of 80.5, and a NLR of 0.25. For ADDwR, they found a Sensitivity of 0.76, Specificity of 0.82, PLR of 3.80 and NLR of 0.36. Based on these findings, they suggested that mUS be incorporated in practice as a rapid screening tool for disc displacement (Li et al., 2012).

A recent systematic review and meta-analysis by Thapar et al. comparing the diagnostic accuracy of mUS to MRI for ID found that of the 14 studies that they analyzed, 5 studies demonstrated high specificity and 9 studies demonstrated high sensitivity (Thapar et al., 2023). They found that the Specificity ranged from 16% to 96% and the Sensitivity ranged from 22% to 85% (Thapar et al., 2023). Overall, the Specificity was found to be consistently higher than the Sensitivity, which suggests that mUS is a useful tool for ruling out TMJ ID (Thapar et al., 2023)

Most studies reviewed agree that US is a useful screening tool, and effective at predicting the presence of disease. They also suggest that if abnormal findings are present, that an MRI still be performed as it allows for multiple views and greater detail of structures. They also largely agree that mUS is not effective in readily diagnosing medial disc displacement.

3.7.3 Juvenile Idiopathic Osteoarthritis

There is a paucity of studies looking at the efficacy of mUS in diagnosing OA of the TMJ. A systematic review by Hechler et al., reviewed mUS compared to MRI in diagnosing patients with Juvenile Idiopathic Arthritis (JIA). Their conclusions were of limited applicability as there was wide variability in both mUS and MRI capture protocols in the studies reviewed. Overall, they found that both Sensitivity and Specificity for mUS was less than 80% when compared to MRI in diagnosing JIA and it was suggested that MRI remain the gold standard and should be pursued if JIA is suspected (Hechler et al., 2017). Another study performed by El-Melegy et al. compared MRI to musculoskeletal mUS in evaluating the TMJ in patients with a known diagnosis of rheumatoid arthritis. They used linear, high-frequency probes (7.5-12MHz) to take images in both open and closed mouth positions. They found that TMJ effusion and disc displacement was detected at a similar rate between mUS and MRI.

MRI was significantly better than mUS when detecting TMJ bony erosions (El-Melegy et al., 2017). We were unable to find any studies looking at mUS in diagnosing patients with other types of arthritis, including OA.

3.8 Patient Procedures

3.8.1 Patient Criteria

Between June 2022 and August 2024, 30 patients were recruited for clinical trials and the 20 patients that completed their MRI scans were included in this study. Patients were screened and recruited at the Department of Oral and Maxillofacial Surgery at the Health Sciences Centre in Winnipeg, Manitoba. These patients presented to our specialty clinic by outside referral from physicians and dentists in the province. Inclusion criteria were patients exhibiting signs and symptoms of TMD following a history and physical. Exclusion criteria was patients under the age of 18, patients unable to consent for themselves and patients with contraindications to having an MRI performed, including those with metallic implants, coronary and peripheral artery stents, cardiac pacemakers, prosthetic heart valve, intrauterine contraceptive devices, and claustrophobia. Informed consent was obtained from each patient by a member of the Oral and Maxillofacial Surgery team.

3.8.2 Clinical examination

The patients included 15 females, and 5 males, of varying ages and clinical examination for TMD was carried out by a member of the Oral and Maxillofacial Surgery team. This included the patient's chief complaint, date of onset of discomfort, pain location, duration, frequency and intensity, and any exacerbating or relieving factor. Tenderness to palpation of the temporalis, masseter, sternocleidomastoid, lateral pterygoid insertion and lateral pole of the condyle was recorded. Maximal incisal opening, lateral excursions and protrusion was also measured. Finally, wear facets, deflections on opening and joint sounds were noted. This information was collected on a survey and diagram during clinical examination and retained for possible statistical analysis and interpretation **(Appendix A).** While not forming part of this thesis, the opportunity remains for it to be analyzed at a later date.

3.8.3 Ultrasonic Imaging

Once informed consent was obtained, HHU examination of the right and left TMJs of each patient was carried out using the Butterfly iQ+ HHU device **(Appendix B).** Images were captured by one of two team members trained in HHU scanning of the TMJ by the ultrasound department at Health Sciences Centre. Real time video images were captured using the MSK – soft tissue preset at a depth of 2cm and gain of +70 in both closed and open mouth positions at 10MHz. As per the Butterfly iQ+ manual, the "MSK-Soft Tissue is our highest-frequency preset. It has been developed with high dynamic range for optimized detail resolution of soft tissue structures, such as intramuscular assessment. It is commonly used by advanced users of MSK point-of-care HHU looking for detailed anatomical assessment. The preset penetrates from a minimum depth of 1cm to a maximum of 12cm." Images were taken with the patient in a seated position, with the probe angled parallel to the zygomatic arch and perpendicular to the long axis of the joint. The right joint was always imaged first, followed by the left. The images were interpreted by the Principal Investigator, who was blind to both clinical examination and MRI results. The surface of the condylar head and articular eminence can be visualized as two hyper echoic lines, while the articular disc appears hypoechoic.

Table 3.8.3 Butterfly iQ Handheld Ultrasound System Specifications

Item	Butterfly iQ	Butterfly iQ+
Probe dimensions	185 x 56 x 35 mm (7.2 x 2.2 x 1.4 in.)	163 x 56 x 35 mm (6.4 x 2.2 x 1.4 in.)
Probe weight	313 grams (.69 lbs)	309 grams (.68 lbs)
Power	Battery (rechargeable)	
Battery Life	≥2 hours in B-Mode (typical new battery at 25°C). ≥2 hours refers to continuous scanning vs. traditional scanning patterns.	
Languages	The user interface and accompanying documentation is localized in English, Spanish, French, German, Italian, Polish, Portuguese, Dutch, Danish, Norwegian, Swedish, and Finnish.	
Display	Variable	
Min/Max scan depth	1 cm min / 30 cm max	
Ultrasound chip	Integrated CMOS chip	
Transducers	~9000-element CMUT	
Frequency Range	1-10 MHz	
Operating system	• Apple devices require iOS 14.0 or newer. Not compatible with beta or unreleased versions. • Google Pixel devices require Android version 10 or newer. • OnePlus mobile devices require Android version 10 or newer. • Samsung mobile devices require Android version 9 or newer.	

CHAPTER 4

4.0 RESULTS

4.1 Statistical Analysis

Statistical analysis was performed using the Statistical Package for Social Sciences (SPSS) version 28.0 to compare MRI findings with HHU diagnosis of disc position and arthritic alterations. Subcategories of disc displacement (with and without decrease) were examined separately and in combination for a comprehensive evaluation. The Fisher's Exact Test was used to compare categorical data and Cohen's Kappa test was used to assess the overall agreement between MRI and HHU using Cohen's Kappa test, with values interpreted as: ≤0 (no agreement), 0.01–0.20 (none to slight), 0.21–0.40 (fair), 0.41–0.60 (moderate), 0.61–0.80 (substantial) and 0.81–1.00 (almost perfect agreement). Diagnostic performance metrics such as Sensitivity, Specificity, Positive Predictive Value (PPV), Negative Predictive Value (NPV) and Accuracy were calculated, Receiver Operating Characteristic (ROC) curves were created to evaluate the Area Under the Curve **(Appendix C and D)** and diagnostic performance parameters like sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV) and accuracy were computed, A p-value of <0.05 was considered statistically significant.

For Right TMJ, the p-value is statistically significant for ADDwoR, and AUC equates that of MRI for diagnosing this condition and equivalent performance to HHU. The test of correlation yielded a p-value < 0.05 and hence, we can conclude that HHU is a valid method to diagnose ADD with reduction and the AUC analysis also confirmed that there is a perfect correlation between HHU and MRI. For arthritic changes, the p value is not statistically significant therefore the HHU cannot be relied on to diagnose the changes and the AUC reveals that diagnostic accuracy is no better than chance. Regarding the Left TMJ analysis for ADD without reduction, the p-values were extremely low, which established the significant and strong correlation between HHU and HHU diagnosis of this condition in addition, the AUC also proved that HHU had perfect agreement in this case with MRI. Likewise, in cases of ADD with reduction, the p-value appendix has a positive correlation implying that the diagnostic reliability of

HHU is high, as asserted by the AUC at 100%. On the other hand, the p-value related to the arthritic changes means that the HHU is less reliable in diagnosing these changes and the AUC shows poor diagnosis ability.

An MRI was completed for each patient in this study using standardized TMJ protocol, which is axial T2 and oblique parasagittal fat-sat proton densities sequences through the TMJs with the mouth closed and mouth open 30mm. Sagittal, axial and coronal slices were provided in T1 and T2-weighted views. Pseudo-dynamic images were provided by stringing together select slices from closed mouth to open mouth positioning. MRIs were read by an independent radiologist blind to this study employed by Shared Health. Results were not accessed by the PI until the conclusion of the study when HHU and MRI results were compared for each patient and a statistical analysis performed. At no point was the PI to the clinical examination or MRI results prior to interpretation of the HHU scans for each patient

Patients complaining of severe TMD were interviewed, examined, and scanned in-clinic by HHU and the results compared to the MRI scans acting as the comparative standard **(Appendix C).** Both the right and left TMJ were scanned, with the diagnoses focussed on determining whether there was an issue with AADwoR, ADDwR, or OA. Sensitivity, Specificity, PPV, NPV, and Accuracy, values were calculated for HHU images in comparison to MRI, with a 95% CI, and min-max values for combined left and right TMJ's **(Appendix D)** and evaluated using Interrater Reliability statistical software **(Appendix E, F, G, H and I) (Table 4.1.1).**

4.1.1 Fisher's Exact Test

Fisher's Exact Test has been applied to all results, and is preferable for smaller data samples, such as the OA data, that do not meet the criteria for the Chi-Square (χ^2) or Phi-Coefficient & Cramer's V test **(Appendix G and I).** Fisher's is a statistical hypothesis test using p-values to assess the difference between the values of two nominal variables. The study determined a strong correlation between HHU and MRI data, and therefore rejected the null hypothesis for ADD, but not for AO.

Table 4.1.1 Summary of diagnostic statistics. Summary of diagnostic statistics obtained from HHU scans when compared to MRI as the standard. Diagnosis includes ADDwoR, ADDwR, and arthritic changes.

	ADDwoR	*ADDwR*	*OA*
Sensitivity	96.8%	76.5%	50.0%
Specificity	100%	100%	89.5%
Accuracy	97.5%	90.0%	87.5%
Positive Predictive Value (PPV)	100%	100%	20.0%
Negative Predictive Value (NPV)	90.0%	85.2%	97.1%
Positive Likelihood Ratio (PLR)	∞ +	∞ +	4.75
Negative Likelihood Ratio (NLR)	.0323	.235	.559
Cohen's Kappa	.931	.789	.231
Chi-Square (χ^2)	34.8	26.1	n.a.
Phi-Coefficient & Cramer's V	.933	.807	n.a.
Fisher's Exact Test	$p < .001$	$p < .001$	$p = .237$

Table 4.1.2 Cohen's Kappa. Cohen's Kappa is a statistical measure used to assess the level of agreement between the two nominal categories of HHU and MRI results, for the three conditions outlined, and accounts for agreement occurring by chance (Appendix F).

	Cohen's Kappa	*Agreement Level*	*Interpretation*
ADDwoR	0.931	Almost Perfect	Indicates very strong agreement between HHU and MRI. Highly reliable for diagnosis.
ADDwR	0.789	Substantial	Strong agreement; reliable, but with moderate false negatives.
OA	0.231	Low	Weak agreement: HHU is not reliable for OA detection, agreement may be due to chance.

Table 4.1.3 Hypothesis Test. Fisher's exact test is a statistical method used to determine if there is a significant association between HHU and MRI results (Appendix I) and is used to test p-values. The study determined a strong correlation between HHU and MRI data, and therefore rejected the null hypothesis for ADD, but accepted the null hypothesis for OA.

	P-value	*Hypothesis Outcome*	*Interpretation*
ADDwoR	< 0.001	Reject Null Hypothesis (accept H_a)	Significant association HHU and MRI results.
ADDwR	< 0.001	Reject Null Hypothesis (accept H_a)	Significant association HHU and MRI results
OA	0.237	Accept Null Hypothesis (accept H_0)	Not a significant association HHU and MRI results

4.2 Anterior Disc Displacement without Reduction

HHU shows promise as an accurate diagnostic modality for TMD's related to ADDwoR **(Table 4.1.4).** The "almost perfect" agreement between HHU and MRI, with Kappa = 0.931 **(Table 4.1.2)** indicates that HHU is a highly reliable diagnostic tool for ADDwoR. The high Sensitivity and Specificity (96.8% and 100%, respectively) of HHU indicates high reliability and the potential to use HHU in clinical settings. The 10% probability of false negatives **(Table 4.1.4)** suggests careful clinical interpretation is necessary regarding negative results. The small sample size used in the analysis means that further studies are recommended.

A p-value of $\alpha = 0.05$ (5%) was used as the threshold for statistical significance, and, if the p-value is $\leq \alpha$, the null hypothesis is rejected. Fisher's Exact Test had a p-value of <0.001 which indicates strong evidence to reject the null hypothesis.

4.3 Anterior Disc Displacement with Reduction

HHU shows promise as an accurate diagnostic modality for TMD's related to ADDwR, as outlined and discussed **(Table 4.2.1).** Based on the statistical analysis, there is strong evidence to reject the null hypothesis that the HHU is not as accurate as MRI for predicting ADDwR. The results indicate a significant and strong association between HHU and MRI results, with HHU demonstrating high sensitivity (100%), specificity (90%), and accuracy (97.5%). We suggest that HHU is an effective diagnostic tool for ADDwR diagnosis and can be used as a reliable adjunct to MRI in clinical practice.

HHU demonstrates perfect Specificity (100%) and PPV (100%) because all positive HHU results were accurate and corresponded to true disease patients. High accuracy (90%) and substantial agreement (Cohen's Kappa = 0.789) with MRI confirm its reliability in diagnosing ADDwR. The limitation of this test is related to the right side TMJ scan (4 false negatives), and the moderate sensitivity (76.5%). The latter indicates HHU missed 23.5% of true positive cases and suggests that some diseased cases may go

Table 4.1.4 ADDwoR Statistical Summary

Sensitivity	*96.8%*	*HHU correctly identified 96.8% of true positive cases of ADDwoR.*
Specificity	100%	HHU perfectly identified all true negatives without any false positives.
Accuracy	97.5%	39 out of 40 cases were correctly classified.
Positive Predictive Value (PPV)	100%	All positive HHU results accurately indicated true cases of ADDwR.
Negative Predictive Value (NPV)	90%	90% of negative HHU results accurately indicated the absence of the condition.
Prevalence	77.5%	ADDwoR was present in 77.5% of the study population. Adjusted for serious cases in the population at random, prevalence is 2.5% X 62% = 1.55%
Positive Likelihood Ratio (PLR)	∞ +	A positive result strongly confirms the presence of ADDwoR.
Negative Likelihood Ratio (NLR)	0.0323	A negative result moderately reduces the likelihood of disease.
Cohen's Kappa	0.931	Substantial agreement between HHU and MRI results.
Chi-Square (χ^2)	34.8	Significant association between HHU and MRI results. ($p < .0001$)
Phi-Coefficient & Cramer's V	0.933	Strong relationship between HHU and MRI results.

undetected. There were no false positives observed, indicating HHU does not over-diagnose this condition, and there is a need for caution in interpreting negative results due to moderate NPV (85.2%).

The chi-square test ($\chi^2 = 26.1$, $p < 0.001$) and the Phi-coefficient and Cramer's V (0.807) confirm a strong and statistically significant association between HHU and MRI results **(Appendix G).** The high significance supports the validity of the HHU as a diagnostic tool for ADD conditions.

4.4 Osteoarthritis

HHU does not show promise as an accurate diagnostic modality for TMD's related to OA, as outlined **(Table 4.3.1).** HHU has limited diagnostic effectiveness for OA, showing a sensitivity of 50%. It fails to detect half of true positive cases, highlighting significant diagnostic limitations. A PPV of 20% reflects a high rate of false positives and makes HHU unsuitable for reliably confirming OA presence in clinical practice. The Cohen's Kappa value of 0.231 also reveals weak agreement between HHU and MRI findings. This result emphasizes inconsistencies in HHU diagnostic performance and HHU proves inadequate as an independent diagnostic tool for OA assessment.

There was insufficient data to calculate the Chi squared statistic for OA, and therefore Fisher's Exact Test results ($p = 0.237$) were used, and suggest no significant association between HHU and MRI. The lack of statistical significance indicates that observed agreements are likely by chance. This weak relationship further undermines the reliability of HHU for OA diagnosis. Although the positive test results of 20% provide some diagnostic information, it remains insufficient for reliable confirmation. The negative test results do not offer the confidence required for diagnostic accuracy.

4.4.1 Likelihood Ratios

The likelihood ratio is an indication of how likely a test is to be correct. A positive likelihood ratio (PLR) indicates how much a positive results increase the probability of OA being present, while a negative likelihood ratio (NLR), indicates how much a negative result decreases the probability of OA not being present **(Table 4.3.1.1).**

Table 4.2.1 ADDwR Statistical Summary

Sensitivity	*76.5%*	*HHU correctly identified 96.8% of true positive cases of ADDwR.*
Specificity	100%	HHU perfectly identified all true negatives without any false positives.
Accuracy	90%	36 out of 40 cases were correctly classified.
Positive Predictive Value (PPV)	100%	All positive HHU results accurately indicated true cases of ADDwR.
Negative Predictive Value (NPV)	85.2%	85.2% of negative HHU results accurately indicated the absence of the condition.
Prevalence	42.5%	ADDwR was present in 42.5% of the study population.
Positive Likelihood Ratio (PLR)	∞ +	A positive result strongly confirms the presence of ADDwR.
Negative Likelihood Ratio (NLR)	0.235	A negative result moderately reduces the likelihood of disease.
Cohen's Kappa	0.789	Substantial agreement between HHU and MRI results.
Chi-Square (χ^2)	26.1	Significant association between HHU and MRI results ($p < 0.001$).
Phi-Coefficient & Cramer's V	0.807	Strong relationship between HHU and MRI results.

Table 4.3.1 OA Statistical Summary

Sensitivity	*50%*	*HHU correctly identified 50% of true positive OA cases.*
Specificity	89.5%	HHU accurately identified 89.5% of true negative cases.
Accuracy	87.5%	35 out of 40 cases were correctly classified.
PPV	20%	Only 20% of positive HHU results corresponded to true OA cases.
NPV	97.1%	97.1% of negative HHU results correctly ruled out arthritis.
PLR	4.75	Moderate ability to confirm disease when the result is positive.
NLR	0.559	Limited ability to rule out disease when the result is negative.
Cohen's Kappa	0.228	Low agreement between HHU and MRI results.
Fisher's Exact Test	p = 0.237	No significant relationship and fail to reject null hypothesis between HHU and MRI results.

Table 4.3.1.1 Likelihood Ratios. Positive and Negative Likelihood Ratios explain how much a positive test result increases the probability of OA, or how much a negative test result decreases the probability of a OA.

	Value	Interpretation
PLR	4.75	A PLR >1 indicates the test is useful in identifying the disease when positive.
		A PLR closer to 10 or higher is considered excellent. At 4.75, this test has a moderate ability to increase the likelihood of disease with a positive result.
NLR	0.559	An NLR <1 indicates the test is useful in ruling out the disease when negative.
		An NLR closer to 0.1 or lower is desired for strong "rule-out." At 0.559, this test has a moderate ability to decrease the likelihood of disease when negative.
Post-Test Probability	Positive: 20%	After a positive test, the probability of disease increases from 5% to 20%.
	Negative: 3%	After a negative test, the probability of disease decreases from 5% to 3%.
Implications	Moderate	A positive result moderately increases the likelihood of disease but may require further confirmation.
		A negative result moderately decreases the likelihood of disease but not accurate
Decision	Dependence on PLR & NLR	Higher PLR and lower NLR values would improve diagnostic reliability.
		Current values indicate the test is moderately useful but not accurate.

4.4.2 Fisher's Exact Test

The p-value was obtained for both left and right TMJs to assess OA and is greater than 0.05 and thus there is no statistically significant association between the ultrasound and MRI results. HHU cannot be relied on to detect or diagnose OA changes:

P value calculation

Fisher's Exact Test: The p-value is 0.237, no significant association between MRI and HHU results for detecting OA (at a typical $\alpha = 0.05$ level).

Comparative Measures:

Odds Ratio: 0.118 (95% CI: 0.0061 to 2.27). This suggests a low likelihood of agreement between HHU and MRI in detecting arthritis, but the wide confidence interval shows high uncertainty due to small sample size.

Relative Risk: 0.211 (95% CI: 0.0397 to 1.12): Indicates that individuals testing positive for OA via MRI are less likely to test positive HHU using US. The confidence interval crossing 1 suggests the lack of statistical significance.

Interpretation of p-values:

1. There is a weak agreement between MRI and HHU in detecting OA, as reflected by the low odds ratio and the nominal measures.
2. The lack of statistical significance in the Fisher's Exact Test ($p = 0.237$) suggests that any observed differences between MRI and HHU results could be due to chance rather than a systematic difference.

The wide confidence intervals for both the odds ratio and relative risk indicate variability and uncertainty in the estimates, maybe due to the small sample size.

4.5 Chi Squared Test and Contingency Tables

The chi-square test is a statistical procedure that compares observed data to expected data to determine if a difference is due to chance or a relationship between variables. This test is acceptable for ADDwoR and ADDwR, but is not valid for OA, as the data for the latter did not fit the test requirements (population size). Statistical significance for OA was performed using the Fisher's Exact Test only.

The chi-square test and the Phi-coefficient and Cramer's V confirm a strong and statistically significant association between HHU and MRI results for ADDwoR and ADDwR. The high significance supports the validity of HHU as a diagnostic tool for this condition. A positive HHU result is highly reliable and can confirm ADD without requiring MRI verification. A negative HHU result for ADDwR, while reducing the likelihood of disease, may still require confirmation with MRI due to the moderate sensitivity and NLR.

HHU has excellent diagnostic performance for ADDwoR and ADDwR, with complete specificity and high reliability when confirming positive cases. However, its moderate sensitivity indicates the need for MRI confirmation in negative cases.

CHAPTER 5

5.0 DISCUSSION

5.1 Overview

In this study, MRI performed in patients with a normal disc-condyle relationship demonstrated the posterior band of the disc located at approximately 11:30-12 o'clock in relation to the condylar head in closed mouth position. In the open mouth position, the condylar head translated forward out of the articular fossa and the disc remained between the eminence and condylar head (**Figure 5.1.1.).** Patients with a normal disc-condylar relationship demonstrated a patent joint space which was maintained in both open and closed mouth positions on the Butterfly iQ+ HHU image. Both the condylar head and articular eminence can be identified as opposing hyperechoic structures with a hypoechoic space in between corresponding to the joint space. A hypoechoic structure corresponding to the articular disc can also be visualized within the space. In addition, the condylar head was able to translate freely during opening and closing in these patients (**Figures 5.1.2. and 5.1.3.**).

In patients with ADDwR, MRI demonstrated that the posterior band of the disc was located anterior to the 11:30 position of the condylar head and the intermediate zone anterior to the articular eminence in closed mouth positioning. Upon opening, the disc is recaptured and sits between the condyle and articular eminence **(Figure 5.1.4.).** Butterfly iQ+ handheld HHU demonstrated reduced joint space in closed mouth position with a hypoechoic structure representing the disc located anterior to the condylar head **(Figure 5.1.5.).** On opening, the joint space appears to increase with recapture of the disc between the articular eminence and condylar head **(Figure 5.1.6.).** The amount of opening prior to recapture depends on the patient however it is more readily identified on HHU due its dynamic nature.

On MRI, patients with ADDwoR demonstrated that the posterior band remained anterior to the 11:30 position of the condylar head in closed mouth position. In open mouth position, the intermediate zone of the disc is not recaptured and remained anterior to the condyle **(Figure 5.1.7.).** In patients with

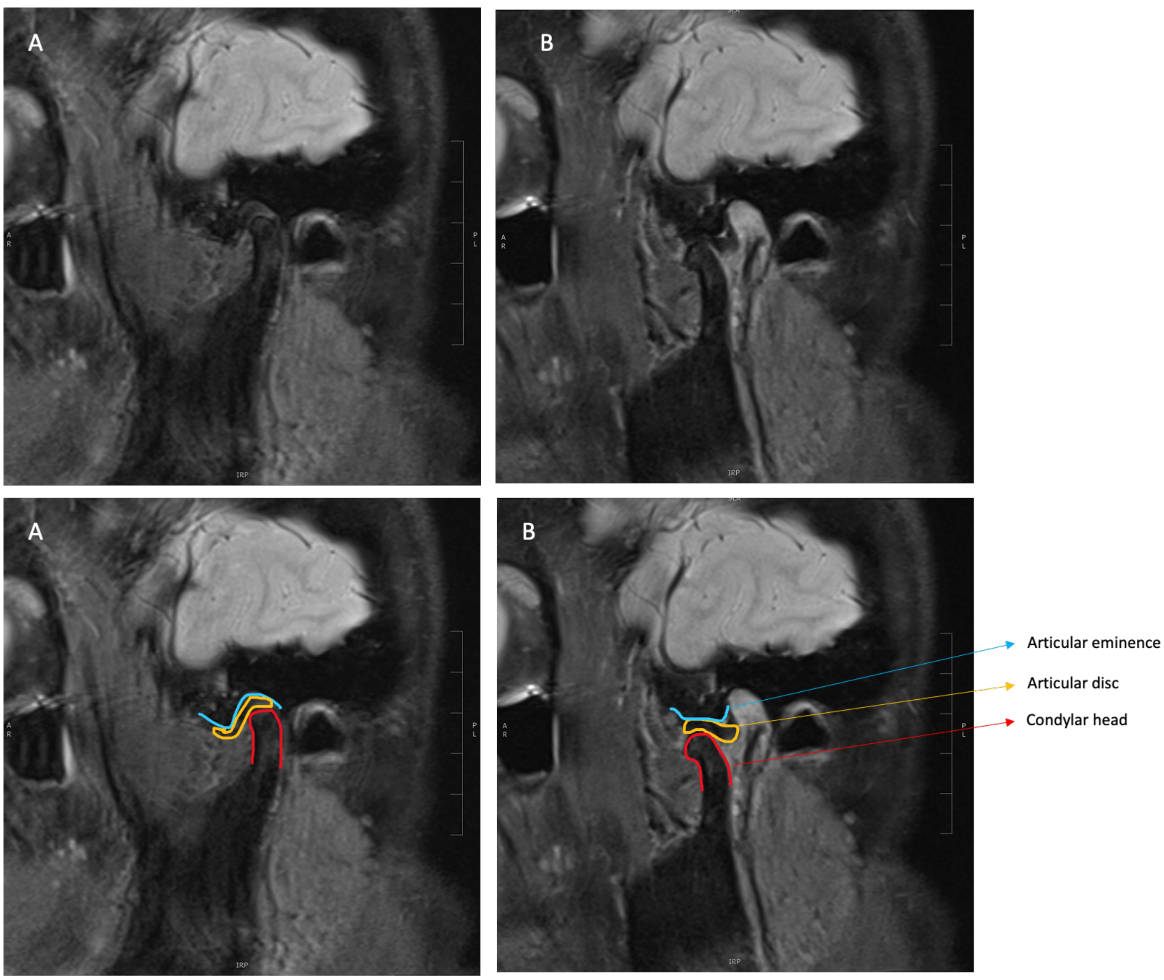

Figure 5.1.1. MRI view of TMJ showing normal TMJ. MRI sagittal view of TMJ showing normal TMJ-disc relationship in both A) closed and B) open position.

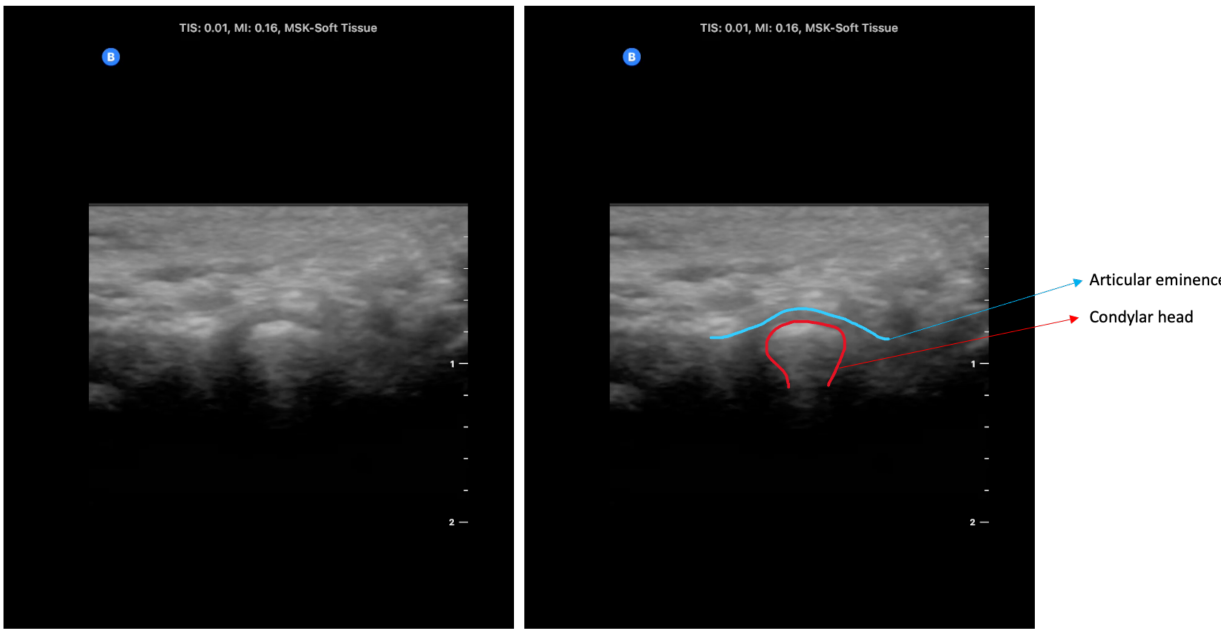

Figure 5.1.2. Normally positioned disc in mouth closed position. Note the round condylar head and patent joint space.

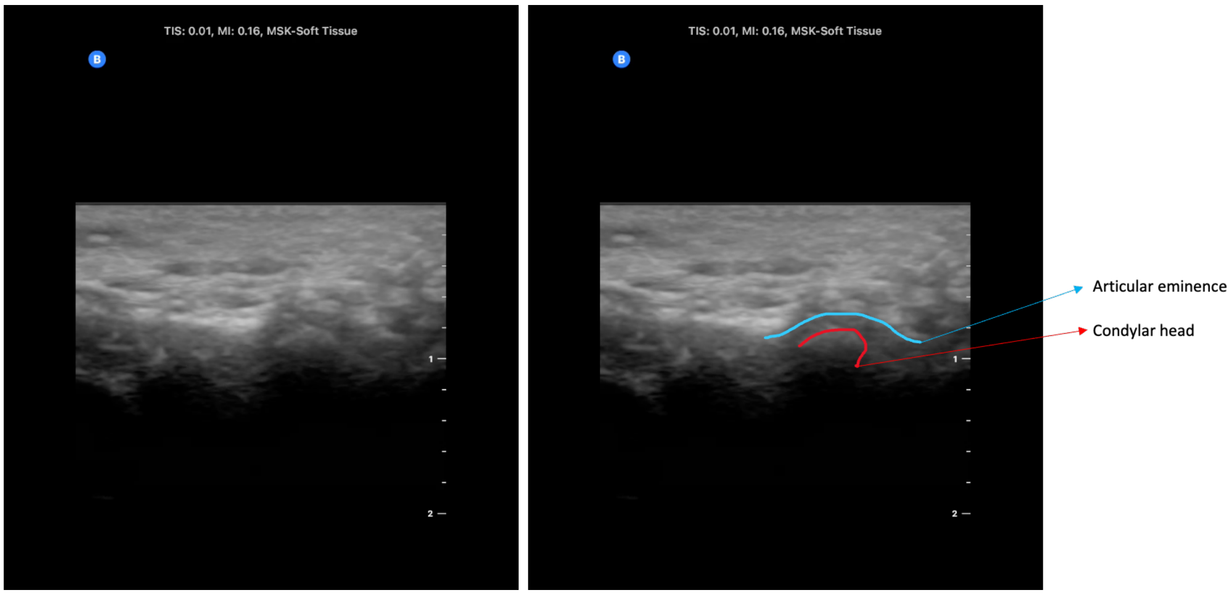

Figure 5.1.3. Normally positioned disc in mouth open position. Note the maintained joint space on translational movement.

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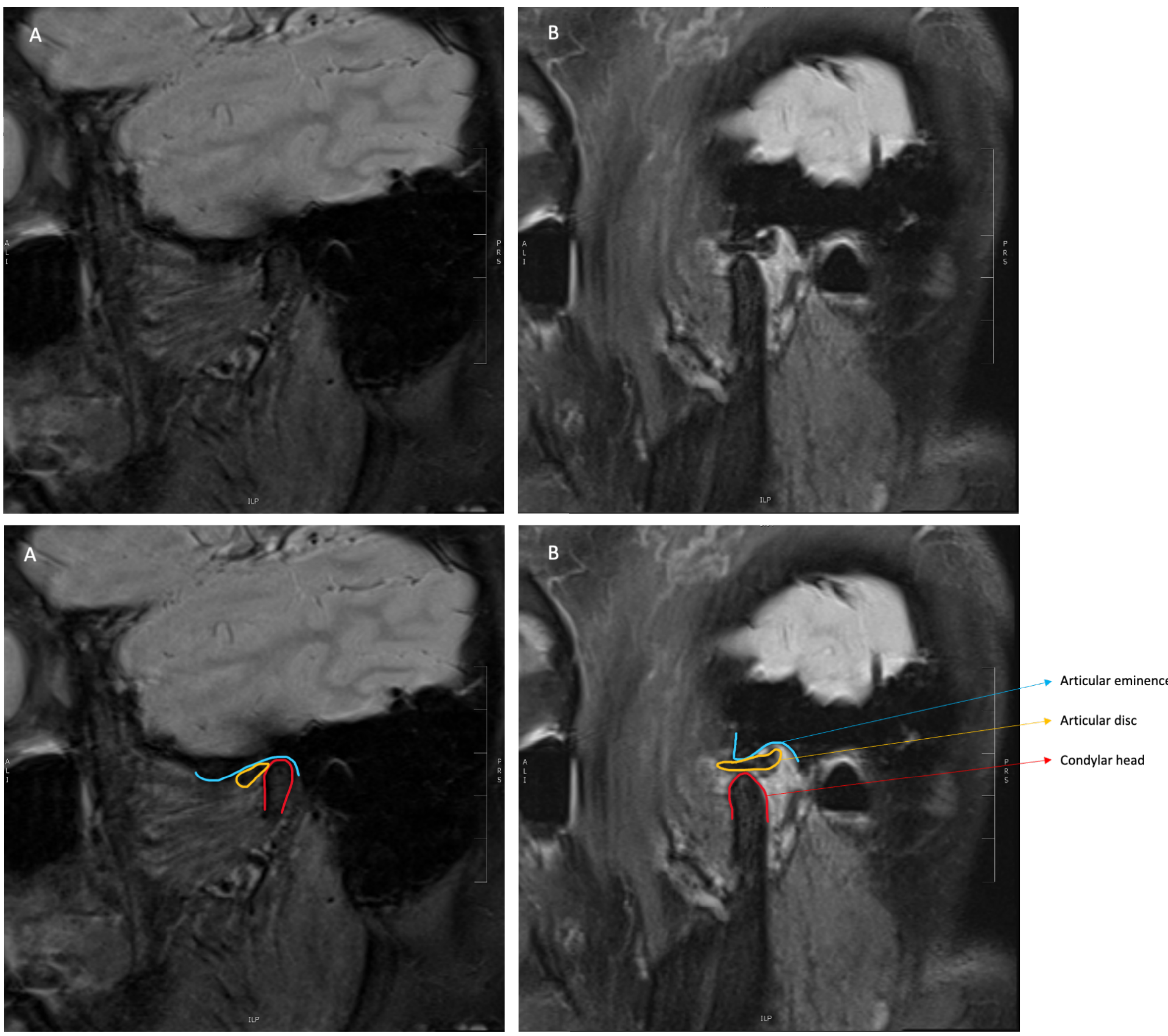

Figure 5.1.4. MRI sagittal view of right TMJ. MRI sagittal view of right TMJ demonstrating A) ADD in closed position and B) adequate recapture of the disc on opening.

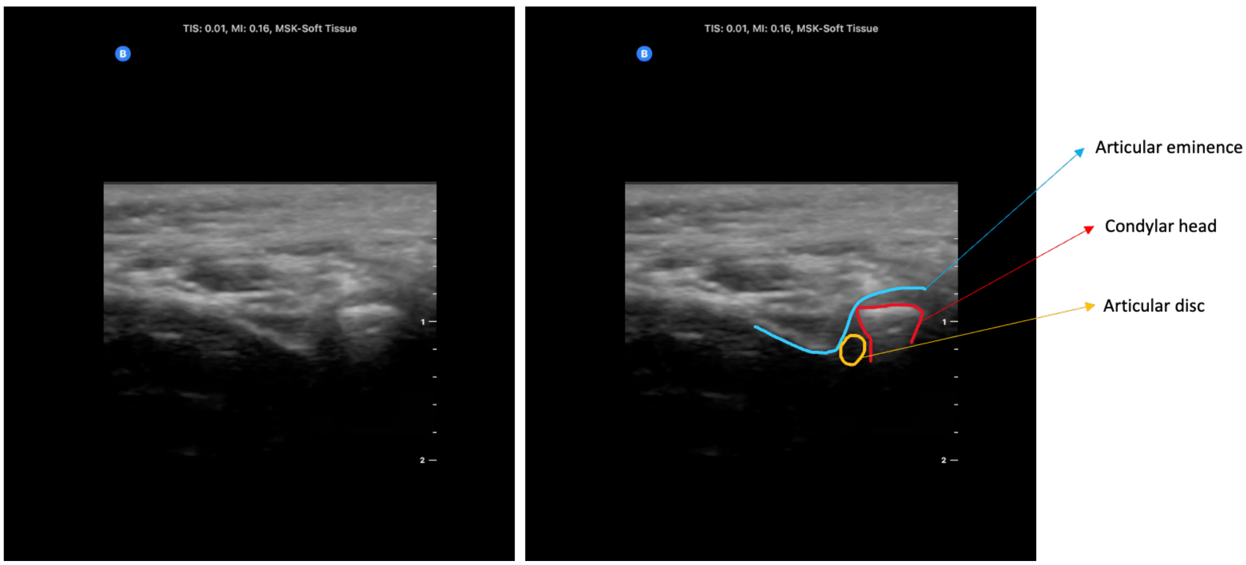

Figure 5.1.5. ADD in closed mouth position. Note the hyperechoic area anterior to the condylar head corresponding to the articular disc. There is also condylar head flattening and reduced joint space consistent with osteoarthritic changes.

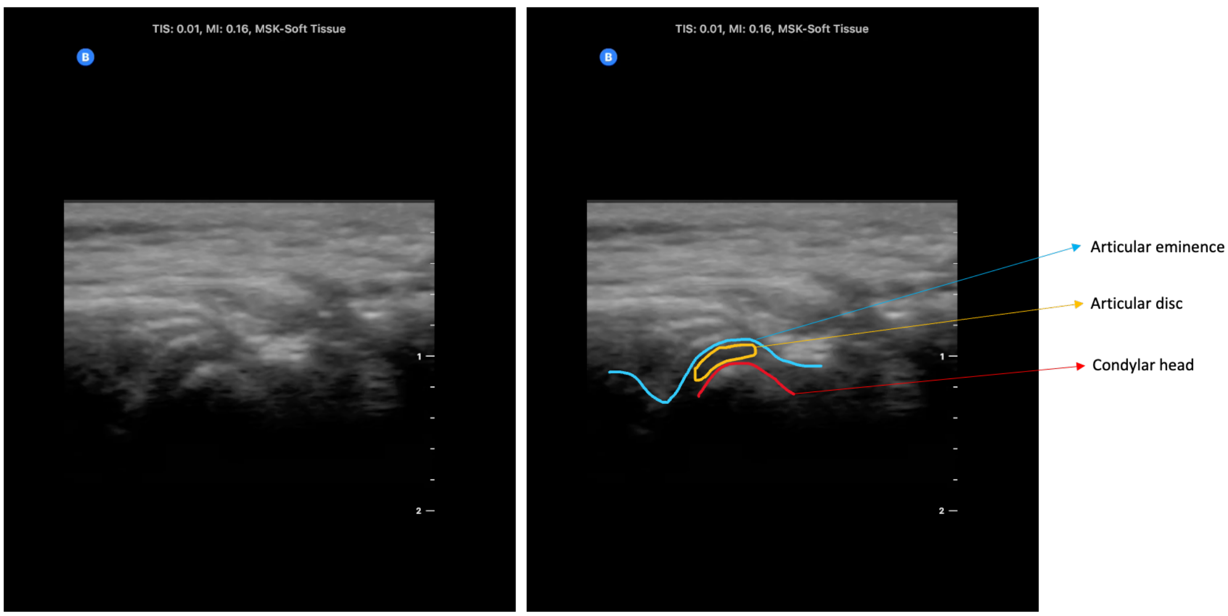

Figure 5.1.6. ADDwR in an open mouth position. ADDwR in an open mouth position in the same patient as in Figure 5.1.5. Note the hyperechoic area superior to the condylar head corresponding to the articular disc.

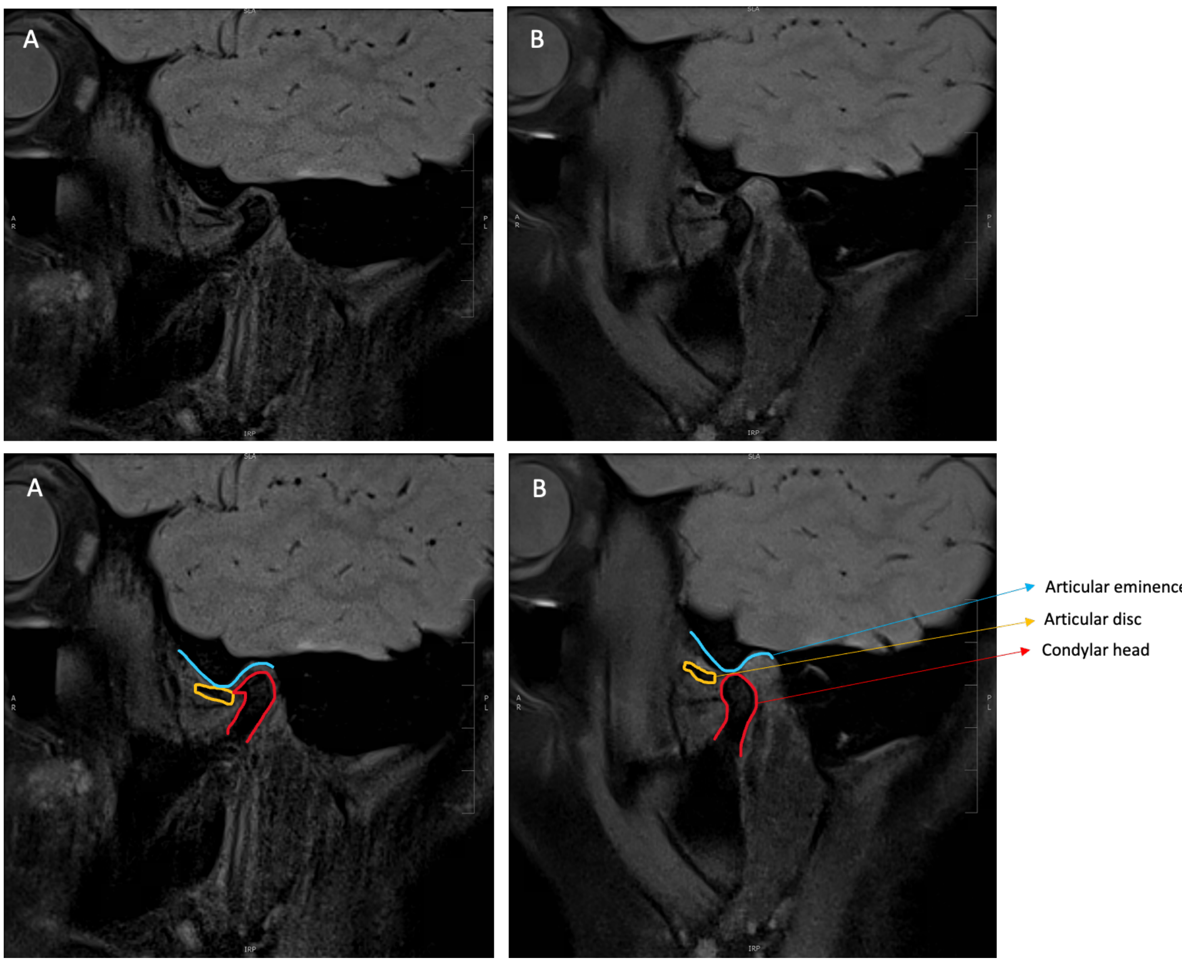

Figure 5.1.7. MRI sagittal views of left TMJ. MRI sagittal views of left TMJ in A) closed mouth and B) open mouth positions. Note the persistent ADDwoR.

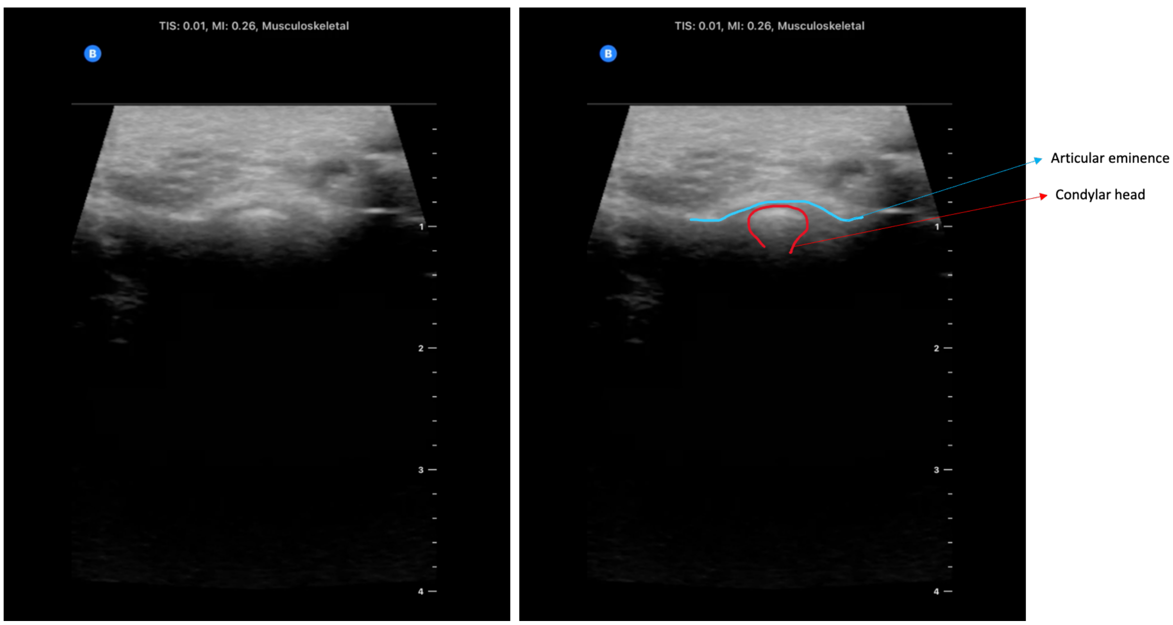

Figure 5.1.8. ADD in closed mouth position. Note the minimal joint space between the articular eminence and condylar head.

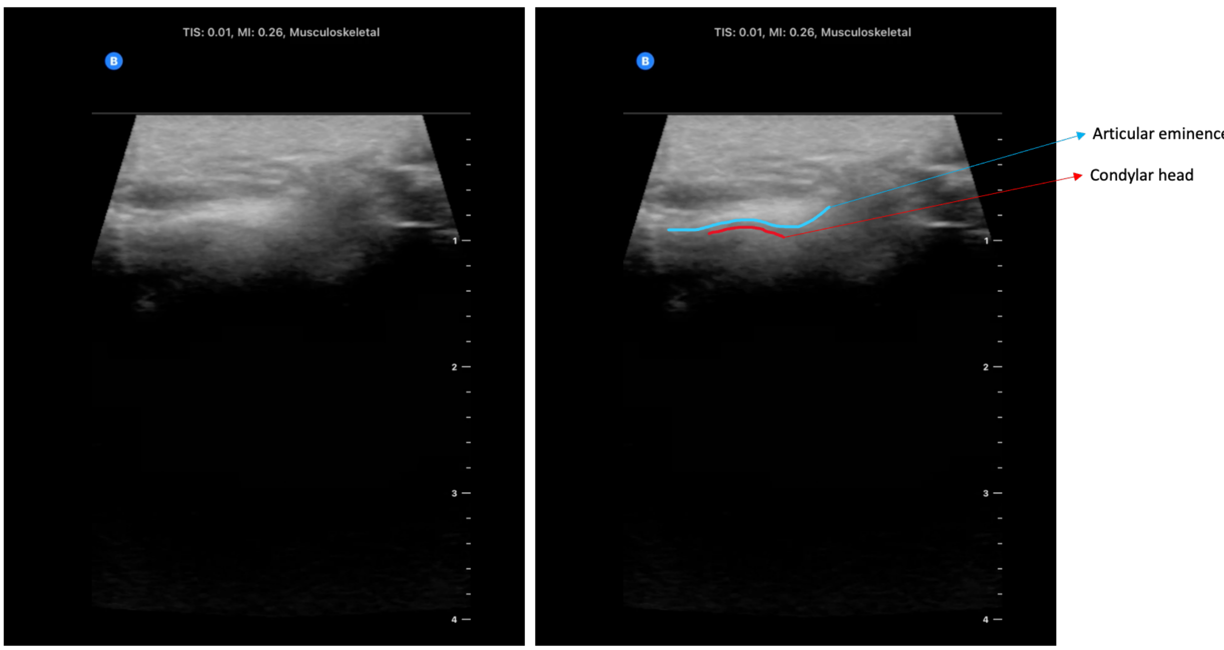

Figure 5.1.9. ADDwoR reduction. ADDwoR reduction on the same patient as in Figure 5.1.8. viii. Note minimal translation of the condylar head on opening and maintenance of the reduced joint space despite rotational movement.

with ADDwoR, Butterfly iQ+ demonstrated loss of joint space in both closed and open mouth positions, signifying that the disc was unable to reduce during translation (**Figures 5.1.8. and 5.1.4).** In addition, there was reduced translation of the condyle on the affected side as compared to the patient's other side, with the exception of those who had internal derangement on both sides. However, the disc as a delineated hypoechoic structure was not always able to be identified.

In patients with arthritic changes of the joint, MRI demonstrated flattening and anterior lipping of the condylar head **(Figure 5.1.10.).** Bilateral joint effusions were also visualized in one patient with bilateral arthritic changes to their joint **(Figure 5.1.12.).** Ultrasound demonstrated both markedly reduced joint space and an irregularly shaped condylar head **(Figure 5.1.11.).** Findings of both low and high-inflammatory OA include loss of joint space, erosion of the condylar head, flattening of the articular eminence and possible subchondral cysts on MRI (Bhargava, 2021). In our study, the Butterfly iQ+ HHU was able to demonstrate these findings, but no subchrondral cysts were identified on MRI or HHU.

There are some findings that are not able to be evaluated with HHU, handheld or otherwise, such as meniscal degeneration or disc perforation. Therefore, MRI would be necessary in these patients in addition to a detailed clinical examination. Only one patient in this study demonstrated severe disc degeneration and query perforation on MRI, which was not picked up by HHU interpretation.

5.2 Diagnostic Indicators

In this study, the disc was not always clearly visible when using the handheld ultrasound, so other diagnostic indicators were also used to formulate a diagnosis. The easiest markers to locate on HHU are the condylar head, which is visualized as a rounded hyperechoic line due to cortical bone, and the articular surface, which also shows as a hyperechoic line opposing the condylar head. Between these two lines, a determination of the joint space can be made. In addition, the position of the condyle within the fossa can be easily identified. Gaten et al., (2004) and Bardhan et al., (2012) found that the condyle is located more posteriorly and superiorly in patients with ADD (Gaten et al., 2004; Bardhan et al., 2012). Reasons for this are multiple, including that the condyle is pushed posteriorly by the anteriorly-located disc, remodeling of the condyle and articular fossa occurs over time, and the condyle is naturally more posteriorly positioned in patients with anterior disc displacement. However, some controversy still exists in regards to posterior displacement being a reliable diagnostic indicator for anterior disc displacement, with studies showing it to be present in around 60% of patients with ADD (Incest et al., 2004).

A study by Dalili et al. found that the mean superior joint space was 3.4mm and 3.2mm on the left and right sides, respectively, when measuring CT scans of patients with asymptomatic joints and no diagnosis of internal derangement (Dalili et al., 2012). They also found a large variation in the positioning of the condyle in the glenoid fossa, however they determined that 92.5% of asymptomatic patients have a condyle that is located centrally in the fossa. This determination was done by comparing the geometric center of the glenoid fossa and condylar head and evaluating if they aligned (Dalili et al., 2012). Hu et. al (2017) found that the superior joint space was increased significantly, approximately 2mm, following disc repositioning procedures in patients with ADD (Hu et al., 2017). This is likely because the posterior band and bilaminar zone are thinned overtime as a result of continued function leading to decreased joint space, and repositioning the disc aided in reopening the space. Therefore, joint space is increased when disc recapture occurs (Hu et al., 2017).

Based on these previous studies, positioning of the condylar head within the fossa and joint space in closed and open mouth positions were used as diagnostic indicators for internal derangement on ultrasound capture. This was useful for cases where the disc was not directly visible. For posterior positioning, a line was drawn down the centre of the condyle and the centre of the glenoid fossa, and they were compared to one another. If the condylar head line was found posterior to the glenoid fossa line, this was indicative of internal derangement **(Figure 5.2.2.).** For joint space, the affected joint space was this compared to the contralateral side. Decreased joint space was another diagnostic indicator of internal derangement. This comparison is not possible when the patient has internal derangement bilaterally.

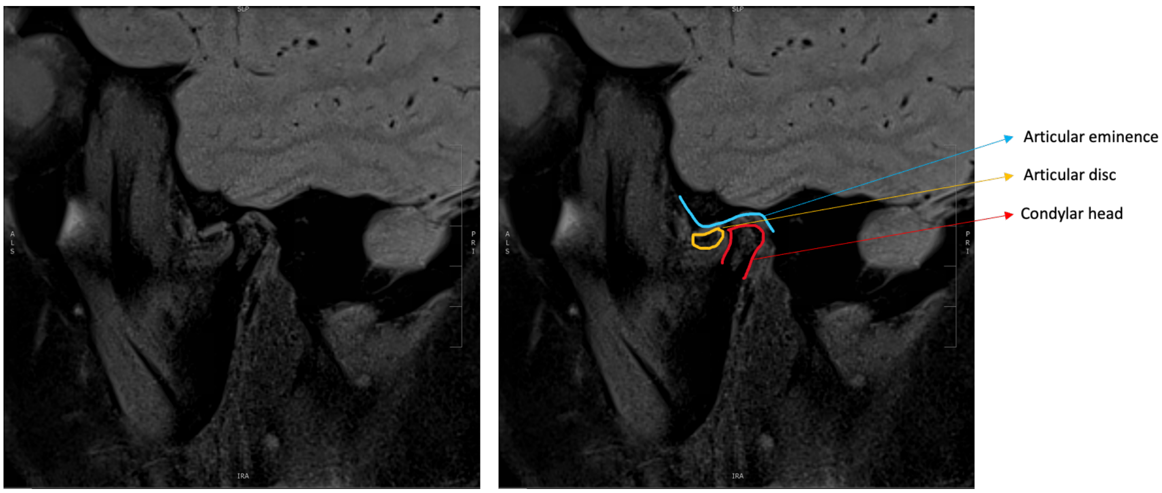

Figure 5.1.10. Sagittal MRI. Sagittal MRI demonstrating OA of the right TMJ with ADD on a closed mouth view. Note the flattening and anterior lipping of the condylar head.

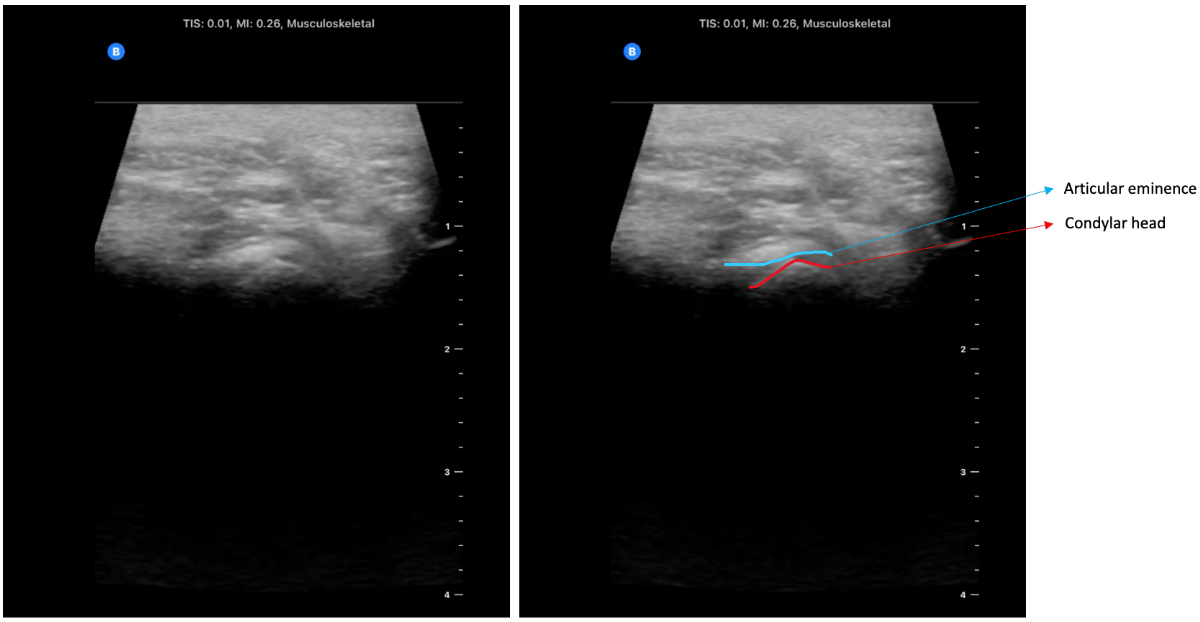

Figure 5.1.11. Ultrasound demonstrating osteoarthritic changes. Ultrasound demonstrating osteoarthritic changes of TMJ in closed mouth position. Note the reduced joint space and irregularly shaped condylar head, thought to represent lipping.

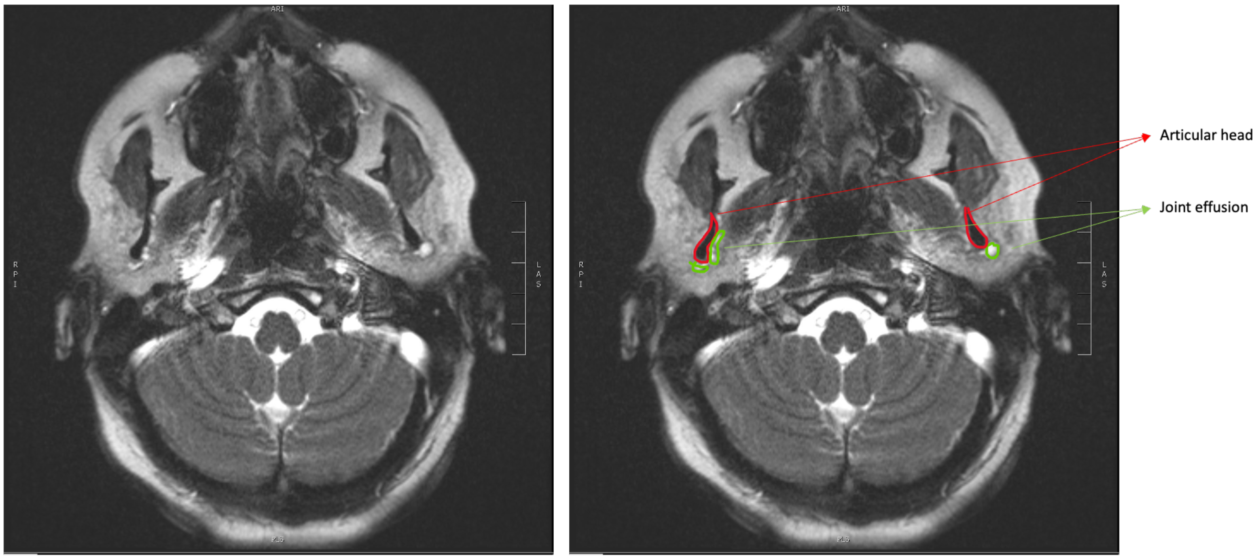

Figure 5.1.12. T2-weighted MRI coronal view. T2-weighted MRI coronal view demonstrating bilateral joint effusions.

A downfall to these methods is that the placement of the lines may vary between clinicians as ultrasound images do not always clearly delineate structures, leading to some variation in interpretation of condylar positioning. It is possible that a higher resolution, at least 12MHz, non-handheld machine with a small linear probe may reveal more detail including clear delineation of the disc; however, these machines are more bulky and costly, less accessible and more difficult to integrate into practice.

5.3 Analysis

Our analysis has found that HHU versus MRI had a sensitivity of 96.77, specificity of 100.0, PPV of 100.0 and NPV of 90.00 when detecting patients with ADDwoR. For ADDwR, HHU had a sensitivity of 76.5, specificity of 100.0, PPV of 100.0 and NPV of 85.2. This means that HHU was overall fairly accurate at correctly identifying patients with ADDwoR, and less so at correctly identifying patients with reduction. HHU was highly accurate at correctly identifying patients that do not have ADD with or without reduction on MRI, meaning that it was useful for identifying patients with a normal disc-condyle relationship. The high PPV also means that patients that are identified as having ADD with or without reduction on HHU are very likely to also be diagnosed with internal derangement on MRI. The calculated p-values were 0.0001 for ADD without reduction and 0.0043 for ADD with reduction. Therefore, we can reject the null hypothesis and conclude HHU is a sufficient modality for accurate diagnosis of disc derangement when it is present.

A recent systematic review and meta-analysis by Thapar et al. comparing the diagnostic accuracy of HHU to MRI for internal derangement found that of the 14 studies that they analyzed, specificity ranged from 16 to 96% and the sensitivity ranged from 22 to 85% (Thapar et al., 2023). Another systematic review by Li et al. looking at 15 studies reported a sensitivity of 0.76, specificity of 0.82 for ADDwR and a sensitivity of 0.79 and specificity of 0.91 for ADD without reduction (Li et al., 2012).

Smaller clinical trials performed by Friedman et al. and Balmacaan et al. found similar results. Friedman et al. reported a sensitivity of 79% and specificity of 100% of 15 MHz US when compared to MRI in diagnosing disc displacements (Friedman, 2020). Balmacaan et al. reported a sensitivity of 72.58% and specificity of 86.84% when using 13MHz US when compared to MRI (Balmacaan et al., 2020). Overall, the specificity was found to be consistently higher than the sensitivity in these studies, which suggests that

US is a useful tool for ruling out TMJ internal derangement. This was also demonstrated in our results for both ADD with and without reduction. This is still highly useful information because it would help clinicians in determining who is to be sent for MRI and possible surgical intervention and who may benefit from conservative measures. It is important to note that the other studies mentioned used high resolution ultrasound. This contrasts with our study, which used a HHU with a larger probe.

HHU was not found to be reliable in diagnosing osteoarthritic changes of the TMJ in our study. The calculated p-value was 0.0125, meaning that we were unable to reject our null hypothesis that HHU is not as accurate as MRI for diagnosis arthritic changes. We also did not have enough data points positive for arthritic changes to make reliable conclusions. There are a couple of different proposed explanations for this. First, osteoarthritic changes were inconsistently reported on MRI reports, and only a few of the reports made mention of these changes despite their presence. To keep MRI readings consistent, only the results stated by the official radiologist on the TMJ MRI report were included in our data analysis and no further interpretation by the clinician was included. Second, it is postulated that our handheld HHU is not of high enough resolution to readily assess for bony changes. Regardless, CT is recommended as the preferred modality for detecting osseous changes and should be ordered if advanced bony degenerative changes are suspected (Atlantean et al., 2018).

There are several reasons why the diagnosis obtained from HHU was not as sensitive and specific as MRI. Firstly, most disc displacements are anterior, however some discs are laterally or medially displaced. A study by Uchida et al. (2015) found that 6.5% of patients had a medially displaced disc, and no patients that they examined had a laterally displaced disc (Uchida et al., 2015). It can be postulated that medial disc displacement will be difficult to localize on HHU due to the increased depth and obfuscation

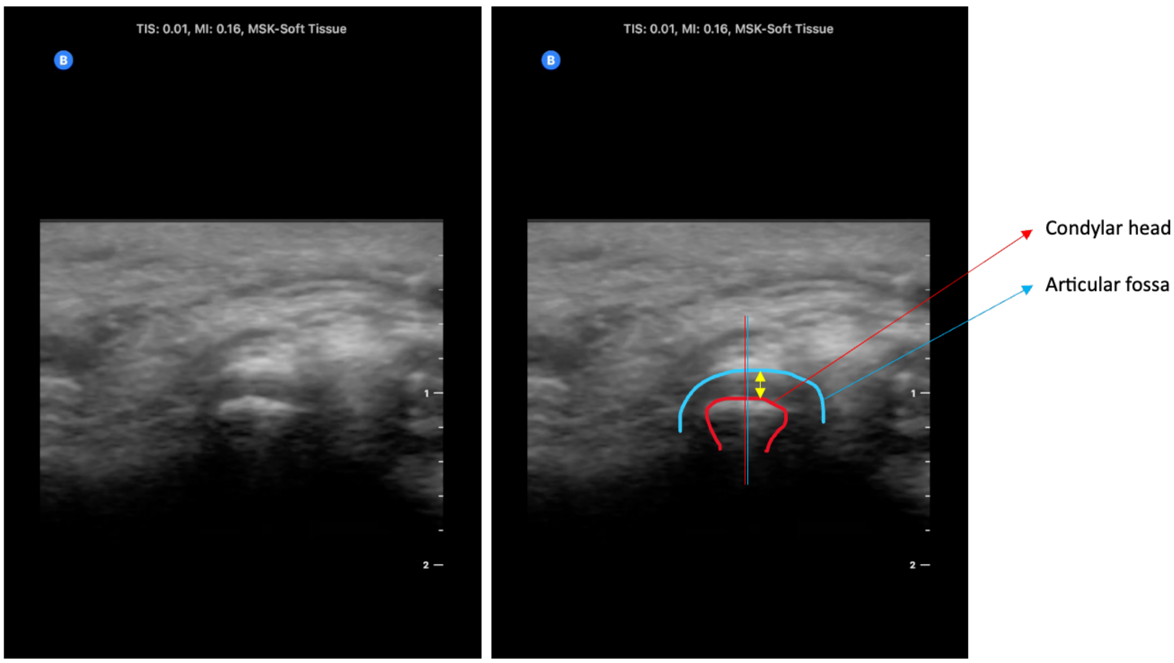

Figure 5.2.1 Ultrasound image of a normal joint. Ultrasound image of a normal joint in closed mouth position demonstrating patent joint space and centric positioning of the condyle within the glenoid fossa. Note that the red line corresponds to the centre of the condylar head and the blue line corresponds to the centre of the glenoid fossa, demonstrating that they are coincident. The yellow arrows indicate joint space.

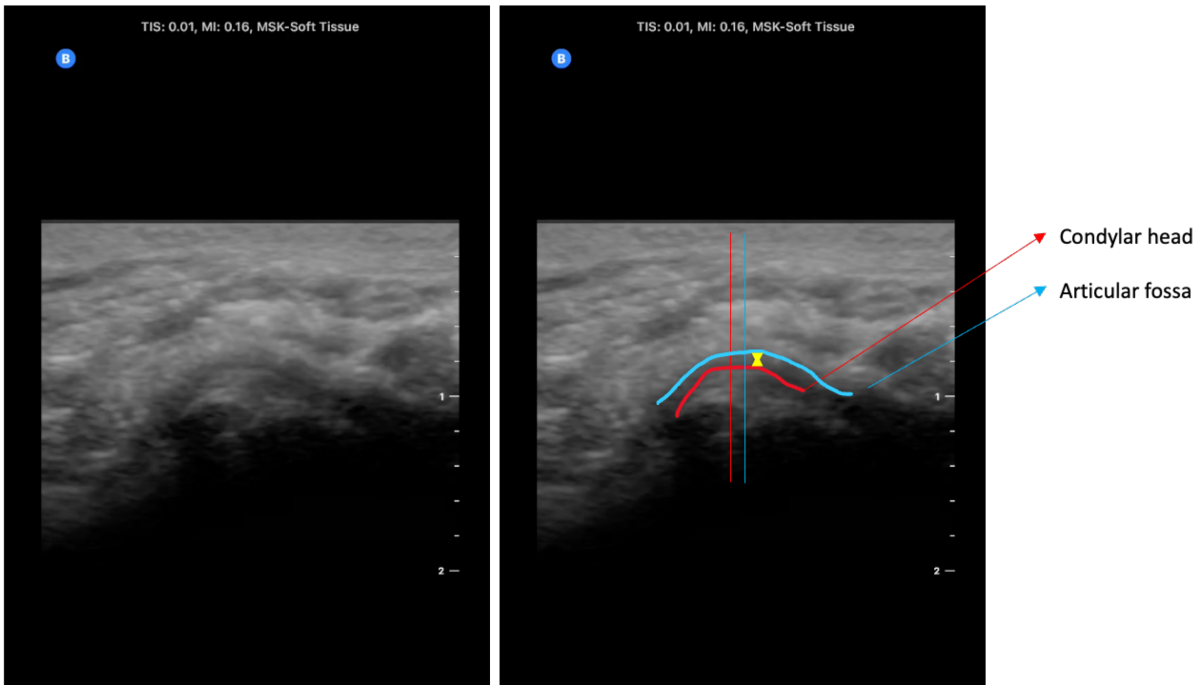

Figure 5.2.2. Ultrasound imaging of TMJ. Ultrasound imaging of the opposite joint in the same patient in Figure 5.2.1**.** in a closed mouth position. Note the decreased joint space and eccentric positioning of the condylar head within the glenoid fossa in a patient with ADDwR. Note that the red line corresponds to the centre of the condylar head and the blue line corresponds to the centre of the glenoid fossa, demonstrating that the condylar head is more posteriorly positioned. The yellow arrows indicate joint space.

from the condylar head and articular eminence. This is not an issue with MRIs as axial, coronal and sagittal views are acquired. Secondly, it is postulated that Wilkes class I and II patients are more difficult to diagnose with HHU, as the joint space and condylar positioning had not changed to a detectable point (Hu et al., 2017). This becomes a larger issue when the disc is not readily visible on HHU This would also explain when HHU was more accurate in identifying patients with ADDwoR than with reduction.

An important factor to consider is that MRI, despite being the current gold standard for diagnosis of internal derangement, does not have a perfect sensitivity or specificity. Tasaki et al. found that MRI was 95% accurate in diagnosing disc position and 93% accurate in diagnosing osseous changes when compared to cryosections of the TMJ from cadavers (Tasaki & Westesson, 1993). The study cited was performed in 1993, so it is likely with modern equipment and imaging techniques in MRI the accuracy has improved. However, there is a paucity of studies evaluating this topic, presumably as it is a difficult and time-consuming task involving meticulous cadaver dissection. Another study done by Al-Arabiya et al. (2016) compared the diagnosis obtained from MRI to direct visualization of the disc using arthroscopy. They found that MRI has sensitivity of 95%, specificity of 88% and accuracy of 94% in comparison with arthroscopy in an analysis of 49 joints (Al-Arabiya et al., 2016). Although we are comparing our results to the current gold standard of MRI, the possibility remains that the MRI interpretation is also incorrect.

5.4 Benefits

According to the Government of Manitoba website, there are only 14 MRI scanners in all of Manitoba, and none of them are located more than a couple hours drive North of Winnipeg. Wait times range from 4 to 14 weeks on average, and radiologists in the hospital predict that the wait times will be closer to 6-9 months, for conditions that are generally lower on the priority list such as TMD. The number of patients waiting for an MRI has also steadily increased each year, with almost 22,000 patients on the waitlist in 2024. Therefore, there is a large portion of the population where MRI is not readily available. In addition, even those living near MRI scanners must deal with long wait times, greatly delaying diagnosis of TMD's and leading to prolonged suffering. This extended wait time also decreased the number of participants for the study as there were 10 patients included in this study that had the ultrasound performed on them yet are still on the MRI waitlist **(Figure 5.4.1.).**

One of the greatest advantages of HHU demonstrated by our study is that it allows for dynamic imaging of the TMJs. MRI series of the TMJs are carried out in static closed mouth and open mouth position at 30mm. Those patients with severe TMJ dysfunction are often unable to open to 30mm, which can make having a TMJ series MRI a painful experience. In addition, some patients maintain a maximal incisal opening greater than 30mm, and their discs may reduce past the 30mm mark. This can lead to a misleading interpretation of MRI, because the radiologist would read the image as non-reducing at 30mm, when in fact the patient has a late reduction of their disc. MRI scans also take much longer than almost any other imaging modality, prolonging discomfort for the patient (Orhan & Aksoy, 2019).

It is the author's opinion that handheld HHU could be very useful in differentiating between myofascial TMJ pain and pain caused from internal derangement, which is often a challenge for clinicians. In turn, this would lessen the burden on the system if ultrasound were used to screen for disc displacement prior to sending for additional imaging. As HHU is highly accurate at identifying those without internal derangement based on our study, those patients who do not appear to have disc displacement on clinical examination or on ultrasound examination may be treated conservatively first prior to resorting to sending for an MRI.

5.5 Limitations

Limitations of this study are that although the ultrasound examiners had received training by the hospital ultrasound department, they were not experts in ultrasound capture or interpretation. However, this demonstrates that POC HHU is accessible and intuitive to many health care providers, including beginners. Another limitation of the study is that due to current MRI wait times, time between initial clinical examination and ultrasound ranged from 15 to 50 weeks. It is possible, though unlikely, that the condition of a patient's TMJs could change in this time. Although MRIs were read independently by a radiologist, we were unable to have the same radiologist interpret each scan by nature of how the hospital system sets up patient appointments for their scans. Finally, evaluation of the joint space and condylar head position was an important factor in formulating a diagnosis for each US. However, there is a paucity of evidence clearly demonstrating that ADD leads to a loss of joint space, although many studies have shown strong correlation (Dalili et al., 2012).

At the conclusion of the study, the decision was made to not analyze and include the survey results. The author's reasoning is that the history and physical examinations were performed by different clinicians, consistency was lacking. A study by Usumez and Guray (2004) found that the diagnostic accuracy of clinical examination was 72% and 81% for ADDwR and ADDwoR, respectively (Usumez & Guray, 2004). Their clinical examination included palpation, measurements and auscultation of joint sounds and their diagnosis was compared to those obtained from MRI. Although clinical examination alone has considerable accuracy, it can be postulated that a formulaic and detailed clinical examination in conjunction with US imaging would lead to very high diagnostic accuracy (Usumez & Guray, 2004). This is an area requiring further investigation in the future.

5.6 Application

Future clinical applications of this research are vast, especially with a handheld machine. Ultrasound is becoming increasingly popular in many facilities across different medical specialties due its ease of use and because it poses virtually no risks to patients. One of the most promising applications is ultrasound-guided surgery, such as arthrocentesis. Currently, arthrocentesis is largely a blind procedure, performed using average measurements from anatomical landmarks. Ultrasound has the potential to lower procedure time, reduce failure rates and lessen procedural and post-operative pain. Bhargava et al., found that the number of attempts for needle insertion using ultrasound-guidance during arthrocentesis was significantly less than conventional methods (Bhargava et al., 2019). A cadaveric study performed by Cha

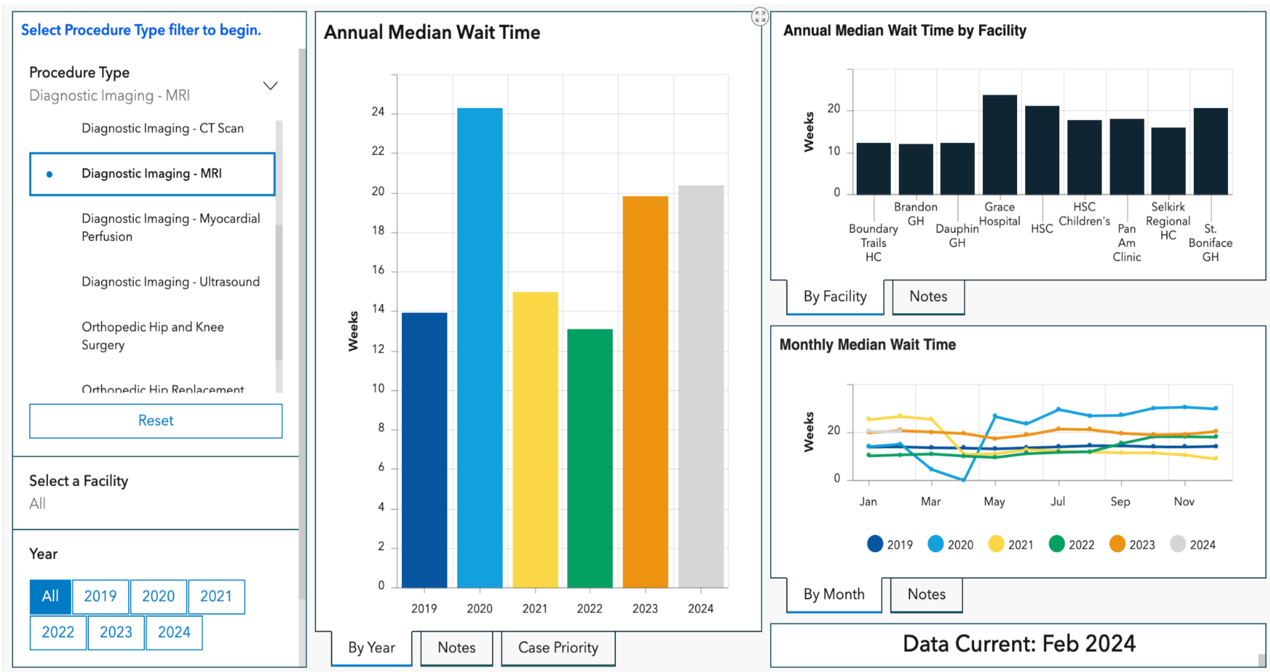

Figure 5.4.1. Annual median wait times. Annual median wait times in the province of Manitoba for MRI of all types. Note that the wait times in 2024 are already the highest of the past 5 years, with the exception of 2020 when the COVID-19 pandemic started (Wait Times in Manitoba, 2024)

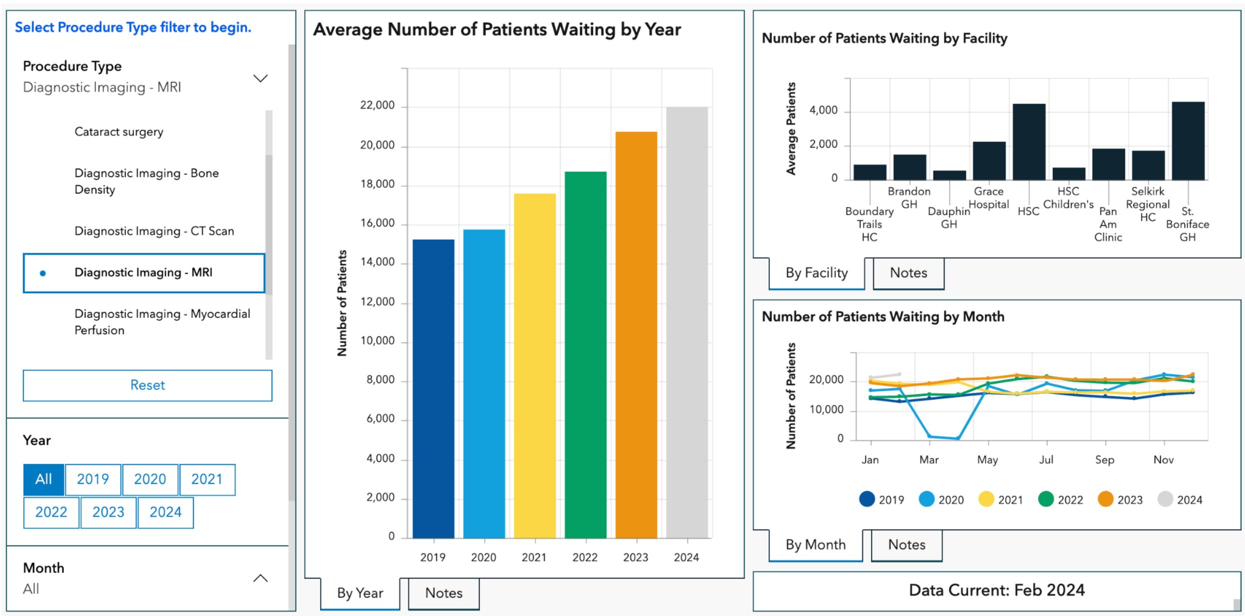

Figure 5.4.2. Patient Wait Times. Average number of patients waiting by year for MRI of all types in the province of Manitoba. Note that the number of patients waiting for diagnostic imaging is continually increasing each year (Wait Times in Manitoba, 2024).

et al., found that the accuracy of US-guided injections was significantly higher than blind injections, at 95% versus 55%, respectively (Cha et al., 2019). Other applications that have been described are guidance of injections such as steroid and autologous blood injections into the TMJ, for fine needle aspiration for cytology and for injection of Botulinum toxin at the correct depth into the masseter and temporalis (Rozylo-Kalinowska & Orhan, 2019). It is the author's hope that HHU be integrated into Oral and Maxillofacial Surgery practices for TMD diagnosis and surgical interventions once it is demonstrated to be a valuable adjunct to current practices. Although capture and interpretation of TMJ pathology may require additional training for the provider, long term benefits are great as it could expedite patient treatment, personalize care, and lessen the burden on the health care system.

5.7 Updating Protocols

It is estimated that 60% to70% of people will experience some form of TMD in their lifetime with up to 5% developing a TMJ disorder serious enough that it interferes with daily activities, such as eating or speaking. The protocol to identify these serious cases includes a referral from dentist or GP, completion of questionnaires such as the Axis I and II questionnaires **(Appendix A and J),** palpitation and other physical exams.

This narrows down the patient population attending the Oral and Maxillofacial Surgery clinic to those in the most severely affected group, including those referred for standard or other non-intervention treatments, and those more likely to require surgical intervention, confirmed by diagnostic imaging. Of this patient population, about 30% are maintained on conservative therapy, without the need for an MRI scan, and 70%, are referred for an MRI scan for confirmation of disease. About 25% of the referred scans indicate that the initial screening was a FP, and that those clients should remain on conservative therapy. The remaining 75% (TP), are considered for more invasive procedures, such as arthrocentesis, arthroscopy, and, in rare cases, open joint procedures. The 25% FP referral rate to MRI is waste of resources that HHU may largely eliminate.

5.8 Financial Impact

This study illustrates that HHU, in addition to normal screening protocols, is of sufficient accuracy to substantially reduce the need for MRI scans by identifying the FP patients that are best maintained on conservative therapy. A flowchart and algorithmic process identifies how to optimize this approach **(Appendix J).** The cost of a single TMJ MRI scan is $800 (Alberta, 2024) using a GE Healthcare 3T Signa architect machine. If HHU can reduce the number MRI exams that resulted in a FP, the potential savings to the Health Care industry are immense (Musculoskeletal (MSK) MRI).

A more robust MRI life cycle costing analysis would need to consider the capital cost of the MRI, including installation, the yearly cost of the physical space in the hospital or private clinic, maintenance and parts, laser film, electricity, salaries and training for technicians, financing, and depreciation, over an approximate ten-year life (Sahu A., 2020). There is also the savings in expense to the client who can attend local clinics rather than travel to more remote facilities.

CHAPTER 6

6.0 CONCLUSIONS

6.1 Anterior Disc Displacement without Reduction

HHU results for ADDwoR have a very high values for Sensitivity of 96.8% and Specificity of 100%, indicating excellent ability to correctly identify both positive and negative cases. Cohen's Kappa of 0.931 indicates almost perfect agreement between HHU and MRI. Fisher's Exact Test p-value < 0.001 confirms a statistically significant association between HHU and MRI. Decision: The HHU is highly reliable for diagnosing ADDwoR and can be considered as an adjunct to MRI.

6.2 Anterior Disc Displacement with Reduction

HHU results for ADDwR have a Sensitivity of 76.5%, meaning that the test identifies patients that have the disease, but with a 23.5% chance of a false negatives. Specificity of 100% is very high and indicates that the test correctly identified all patients that did not have the disease (no false positives). Cohen's Kappa of 0.789 reflects substantial agreement between HHU and MRI and Fisher's Exact Test p-value < 0.001 confirms statistical significance. Decision: The HHU is reliable for diagnosing ADDwR and can be considered as an adjunct to MRI. Due to the incidence of false negatives, further studies using newer HHU devices (improved software, higher MHz), should be conducted, with a view to improving Sensitivity.

6.3 Osteoarthritis

The HHU scans were not able to adequately diagnose OA conditions: Sensitivity is low (50%), indicating poor ability to detect true positive cases and Cohen's Kappa of 0.231 shows weak agreement between HHU and MRI results. Fisher's Exact Test p-value of 0.237 indicates no statistically significant association. Decision: The HHU is not reliable for diagnosing OA and should not be used as an alternative diagnostic tool. It is also noted that MRI has also shown very low values for Sensitivity when diagnosing

OA. It is suggested that the clinician, if OA is suspected, refer the patient to CBCT. HHU scans, and MRI has as the "gold" standard for comparison to HHU results.

6.4 MRI Accuracy

While the HHU diagnostic quality is very good in comparison to MRI, especially for ADDwoR, it is noted that studies have found MRI to have imperfect accuracy, with Sensitivity ranging from 68.9% to 95.3%, and Specificity of 43.1% to 76.1% for TMJ disorders[3,4,5], while CBCT had a Sensitivity of 87.4% and Specificity of 83.2%.[6,7] A recent study (Millón et al, 2024) found that MRI compared to Arthroscopy, for ADDwoR only, had a Specificity of 80.4% and Sensitivity on 84.3%. It is felt that the addition of HHU scans, and subsequent scans by either MRI, CT or CBCT, will substantially improve the conditional probability (Veritasium, 2017) for PPV and NPV of diagnoses.

CHAPTER 7

7.0 RECOMMENDATIONS

7.1 Overview

Subject to further research, and improvements in both the HHU devices and software, HHU should continue to prove its worth as an inexpensive, accurate, and convenient, diagnostic tool. Based on our study results, HHU is a useful screen, when compared to MRI, for diagnosis of ID of the TMJ. HHU is highly accurate when identifying patients without ID and would be useful in determining which patients should be sent for MRI and considered for surgical intervention, and which patients would benefit from conservative therapy.

7.2 Algorithm

It is suggested that protocols for HHU form part of a flowchart and algorithm for determining the optimal diagnostic modalities and course of treatment **(Appendix J).** Patients exhibiting signs and symptoms of TMD should be a referred from a primary care provider to a specialty clinic. Then, patients will complete a series of questionnaires and have a detailed clinical examination performed. At the initial consultation, these patients should also have an HHU performed on their TMJs bilaterally. Based on the findings of the clinical examination and HHU, patients should be divided into those suspected to have ID and those suspected to have a normal disc-condyle relationship. Patients who have a normal disc-condyle relationship should first be treated with conservative measures as their pain is likely to be myofascial in nature. If there is no improvement at follow-up, typically after 3 to 6 months, an MRI for interpretation. For those patients suspected to have serious ID, an MRI will be scheduled, especially if surgical intervention seems likely. Any patients suspected of advanced osseous degeneration or of having TMJ arthritides should be sent for an uninfused CT scan of the TMJs. Following this simple algorithm would lead to an accurate diagnosis of ID in almost all cases. This would lessen the number of patients being sent for unnecessary imaging, allow for faster treatment for the patient, and less burden on the health care system.

CHAPTER 8

8.0 REFERENCES

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APPENDICES

Appendix A

Patient Questionnaire

Tenderness to palpation

Temporalis

Right 0 1 2 3 | Left 0 1 2 3

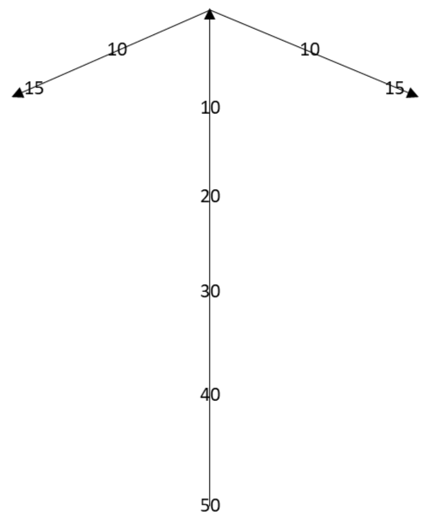
Masseter

Right 0 1 2 3 | Left 0 1 2 3

Sternocleidomastoid

Right 0 1 2 3 | Left 0 1 2 3

Lateral pterygoid insertion



Auscultation

Nature	Right opening	Right closing	Left opening	Left closing
Rubbing				
Clicking				
Grating				

Radiographic examination

Loss of joint space: Right ____mm | Left ____mm

Condylar displacement: Right ____mm anterior ____mm posterior | Left ____mm anterior ____mm posterior

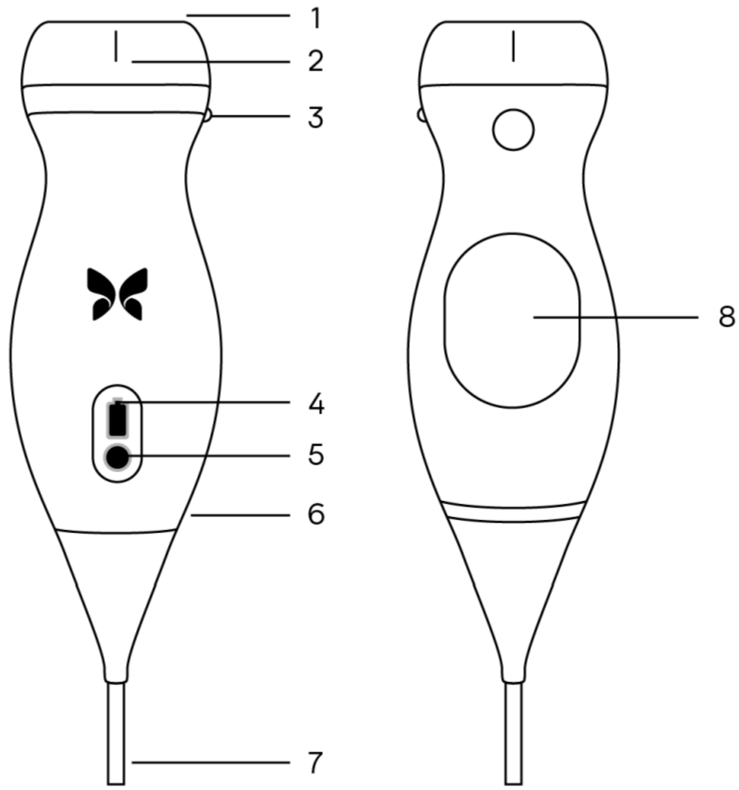
Right condylar flattening: Severe | Moderate | Mild | None

Left condylar flattening: Severe | Moderate | Mild | None

Appendix B

Butterfly IQ+ Diagram

Figure 1. Probe Components



1. Lens
2. Midline Mark
3. Orientation Mark
4. Battery Indicator Lights
5. Battery Indicator Button
6. Probe/Cable Boundary
7. Mobile Device Cable
8. Charging Source

Appendix C

Source Data

This chart summarizes the data set for all HHU and MRI scans, broken down by diagnostic modality, left and right scans of the TMJ, and positive or negative results for the disease under examination.

MRI test

	Right TMJ			Left TMJ		
Patient	AddwoR	ADDwR	OA	AddwoR	ADDwR	OA
1	pos	neg	neg	pos	neg	pos
2	neg	neg	neg	pos	neg	neg
3	neg	neg	neg	neg	neg	neg
4	pos	neg	neg	pos	pos	neg
5	pos	pos	neg	pos	neg	neg
6	pos	neg	pos	pos	neg	neg
7	pos	pos	neg	neg	neg	neg
8	pos	pos	neg	pos	neg	neg
9	pos	pos	neg	pos	neg	pos
10	neg	neg	neg	pos	pos	neg
11	neg	neg	neg	neg	neg	neg
12	pos	pos	neg	pos	pos	neg
13	pos	neg	neg	pos	neg	neg
14	pos	pos	neg	pos	neg	neg
15	pos	pos	neg	pos	pos	neg
16	pos	pos	neg	neg	neg	neg
17	pos	pos	neg	neg	neg	neg
18	pos	neg	neg	pos	pos	neg
19	pos	neg	neg	pos	pos	neg
20	pos	pos	neg	pos	neg	neg

HHU test

	Right TMJ			Left TMJ		
Patient	AddwoR	ADDwR	OA	AddwoR	ADDwR	OA
1	pos	neg	neg	pos	neg	pos
2	neg	neg	neg	pos	neg	neg
3	neg	neg	neg	neg	neg	neg
4	neg	neg	neg	pos	pos	neg
5	pos	pos	pos	pos	neg	neg
6	pos	neg	neg	pos	neg	pos
7	pos	pos	neg	neg	neg	neg
8	pos	pos	neg	pos	neg	neg
9	pos	neg	pos	pos	neg	neg
10	neg	neg	neg	pos	pos	neg
11	neg	neg	neg	neg	neg	neg
12	pos	neg	neg	pos	pos	neg
13	pos	neg	neg	pos	neg	neg
14	pos	pos	neg	pos	neg	neg
15	pos	neg	neg	pos	pos	neg
16	pos	pos	neg	neg	neg	neg
17	pos	neg	neg	neg	neg	neg
18	pos	neg	neg	pos	pos	neg
19	pos	neg	neg	pos	pos	neg
20	pos	pos	neg	pos	neg	neg

Discrepancy: HUU compared to MRI as diagnostic standard

Test Evaluation

Condition			AUC*	Interpretation
Right	TMJ	ADDwoR	0.97	Excellent discrimination; HUU closely matches MRI
Right	TMJ	ADDwR	1.00	Perfect discrimination; HUU perfectly matches MRI
Right	TMJ	OA	0.50	No discrimination; HUU no better than chance
Left	TMJ	ADDwoR	1.00	Perfect discrimination; HUU perfectly matches MRI
Left	TMJ	ADDwR	1.00	Perfect discrimination; HUU perfectly matches MRI
Left	TMJ	OA	0.67	Poor discrimination; HUU moderately matches MRI

*AUC refers to the area under the ROC curve, and measures the quality of HHU as a predictor variable; values can range from .50 (50% chance only) to 1.00 (100%, perfect). Results for left and right were combined for the purposes of statistical analysis.

Raw Data Set (reformat)

	Ultrasound					
	Right TMJ			Left TMJ		
Patient	*ADDwoR*	*ADDwR*	*OA*	*ADDwoR*	*ADDwR*	*OA*
1	✓	×	×	✓	×	✓
2	×	×	×	✓	×	×
3	×	×	×	×	×	×
4	×	×	×	✓	✓	×
5	✓	✓	✓	✓	✓	×
6	✓	×	×	✓	×	✓
7	✓	✓	×	×	×	×
8	✓	✓	×	✓	×	✓
9	✓	×	✓	✓	×	✓
10	×	×	×	✓	✓	×
11	×	×	×	×	×	×
12	✓	×	×	✓	✓	×
13	✓	×	×	✓	×	×
14	✓	✓	×	✓	×	×
15	✓	×	×	✓	✓	×
16	✓	✓	×	×	×	×
17	✓	×	×	×	×	×
18	✓	×	×	✓	✓	×
19	✓	×	×	✓	✓	×
20	✓	✓	×	✓	×	×

✓ Positive on HHU and MRI (agreement)
× Negative on HHU and MRI (agreement)
Negative on HHU, Positive on MRI (False negative)
Positive on HHU, Negative on MRI (False positive)
Advanced arthritic change not identified by HHU

Appendix D

Diagnostic Characteristics

HHU test for ADDwoR

HHU Test		Truth (MRI) ADDwoR +	-	Tot	
	+	30	0	100.00	PPV
	-	1	9	90.00	NPV
	Tot	96.77	100.00	97.50	
		Sensitivity	Specificity	Accuracy	

HHU test for ADDwR

HHU Test		Truth (MRI) ADDwR +	-	Tot	
	+	13	0	100.00	PPV
	-	4	23	85.19	NPV
	Tot	76.47	100.00	90.00	
		Sensitivity	Specificity	Accuracy	

HHU test for OA

HHU Test		Truth (MRI) OA +	-	Tot	
	+	1	4	20.00	PPV
	-	1	34	97.14	NPV
	Tot	50.00	89.47	87.50	
		Sensitivity	Specificity	Accuracy	

Prevalence		ADDwoR	ADDwR	OA
	%	77.5	42.5	5

Appendix E

Likelihood Ratios

	ADDwoR	ADDwR	OA
Sensitivity	96.77	76.47	50.00
Specificity	100.00	100.00	89.47
1-Sensitivity	3.23	23.53	50.00
1- Specificity	0.00	0.00	10.53
PLR	unlimited	unlimited	4.75
NLR	0.03	0.24	0.56

Appendix F

Cohen's Kappa (*k*)

	ADDwoR MRI	
	+	-
+	30	0
-	1	9

Po (observed)	$\frac{39}{40}$			=	0.975
Pa (agree)=	$\frac{30}{40}$	*	$\frac{31}{40}$	=	0.581
Pd (disagree)	$\frac{10}{40}$	*	$\frac{9}{40}$	=	0.056
Pe (tot random)	0.58125	+	0.05625	=	0.638
Kappa (*k*) =	$\frac{\text{Po - Pe}}{\text{1-Pe}}$	=	$\frac{.975 -.6375}{1 - .6375}$	=	**0.931**

	ADDwR MRI	
	+	-
+	13	0
-	4	23

Po (observed)	$\frac{36}{40}$			=	0.900
Pa (agree)	$\frac{13}{40}$	*	$\frac{17}{40}$	=	0.138
Pd (disagree)	$\frac{27}{40}$	*	$\frac{23}{40}$	=	0.388
Pe (tot random)	0.138125	+	0.388125	=	0.526
Kappa (*k*)	$\frac{\text{Po - Pe}}{\text{1-Pe}}$	=	$\frac{.90 - .526}{1 - .526}$	=	**0.789**

	OA MRI	
	+	-
+	1	4
-	1	34

Po (observed)	$\frac{35}{40}$	=		=	0.875
Pa (agree)	$\frac{5}{40}$	*	$\frac{2}{40}$	=	0.006
Pd (disagree)	$\frac{35}{40}$	*	$\frac{38}{40}$	=	0.831
Pe (tot random)	0.00625	+	0.83125	=	0.838
Kappa (*k*)	$\frac{\text{Po - Pe}}{\text{1-Pe}}$	=	$\frac{.975 -.6375}{1 - .6375}$	=	**0.231**

Interpreting Cohen's Kappa

Range		Agreement
0.00	0.09	None
0.10	0.20	Slight
0.21	0.40	Fair
0.41	0.60	Moderate
0.61	0.80	Substantial
0.81	0.99	Near Perfect
1.00	1.00	Perfect

Appendix G

Chi Squared Test and Contingency Tables

Contingency Tables

		ADDwoR			ADDwR				OA			
		HHU				HHU				HHU		
MRI		Negative	Positive	Total		Negative	Positive	Total		Negative	Positive	Total
Neg	Observed	30	1	31	Observed	23	0	23	Observed	34	4	38
	Expected	23.25	7.75	31	Expected	25.5	7.47	23	Expected	33.25	4.75	38
Pos	Observed	0	9	9	Observed	4	13	17	Observed	1	1	2
	Expected	6.75	2.25	9	Expected	11.5	5.53	17	Expected	1.75	0.25	2
Total	Observed	30	10	40	Observed	27	13	40	Observed	35	5	4
	Expected	30	10	40	Expected	27	13	40	Expected	35	5	40

χ^2 Tests

	Value	df	p		Value	df	p		Value	df	p
χ^2	34.8	1	< .001	χ^2	26.1	1	< .001	χ^2	2.71	1	0.1
Likelihood	36.2	1	< .001	Likelihood	31.9	1	< .001	Likelihood	1.8	1	0.18

Comparative Measures

		95% CI				95% CI				95% CI	
	Value	Lower	Upper		Value	Lower	Upper		Value	Lower	Upper
Odds ratio	386*	14.5	10292	Odds ratio	141*	7.04	2825	Odds ratio	8.5	0.441	164

*Haldane-Anscombe correction applied

Appendix H

McNemar Test

Contingency Table (Right TMJ)

	ADDwoR		Total	McNemar Test		ADDwR		Total	McNemar Test		OA		Total	McNemar Test	
Scan	-	+		χ^2	6.37	-	+		χ^2	0.667	-	+		χ^2	15.2
MRI	16	4	20	N	40	10	10	20	N	40	19	1	20	N	40
HHU	15	5	20	df	1	14	6	20	df	1	18	2	20	df	1
Total	31	9	40	p	0.012	24	16	40	p	0.414	37	3	40	p	<.001

Contingency Table (left TMJ)

	ADDwoR		Total	McNemar Test		ADDwR		Total	McNemar Test		OA		Total	McNemar Test	
Scan	-	+		χ^2	5	-	+		χ^2	1.8	-	+		χ^2	11.6
MRI	15	5	20	N	40	13	7	20	N	40	1	19	20	N	40
HHU	15	5	20	df	1	13	7	20	df	1	3	17	20	df	1
Total	30	10	40	p	0.025	26	14	40	p	0.18	4	36	40	p	<.001

Summary for left and right TMJ

Condition	Side	χ^2 Value	p-Value	Conclusion
ADDwoR	Left	1.80	0.180	Good agreement; no significant difference.
ADDwoR	Right	0.667	0.414	Good agreement; no significant difference.
ADDwR	Left	5.00	0.025	Significant difference; poor agreement.
ADDwR	Right	6.37	0.012	Significant difference; poor agreement.
OA	Left	11.6	<0.001	Highly significant difference; poor agreement.
OA	Right	15.2	<0.001	Highly significant difference; poor agreement.

Appendix I

Fisher's Exact Test (OA)

The p-value is obtained for both left and right TMJs to assess arthritic changes is 0.2372 (greater than 0.05) and indicates no statistically significant association between the ultrasound and MRI results.

χ^2 Tests

	Value	p	95% CI Lower	95% CI Upper
Fisher's Exact test		0.237		
Likelihood Ratios				
N	40			
Odds ratio	0.118		0.441	164
Realtive Risk	0.211		0.040	1.12

Comparative Measures:

Odds Ratio: 0.118 (95% CI: 0.0061 to 2.27), suggests a low likelihood of agreement between HHU and MRI in detecting OA, and the wide confidence interval shows high uncertainty due to small sample size.

Relative Risk: 0.211 (95% CI: 0.0397 to 1.12): Indicates that individuals testing positive for OA via MRI are less likely to test positive using HHU. The confidence interval crossing 1 suggests the lack of statistical significance. Phi-coefficient and Cramer's V: Both are 0.260 that provide a weak association between MRI and HHU results.

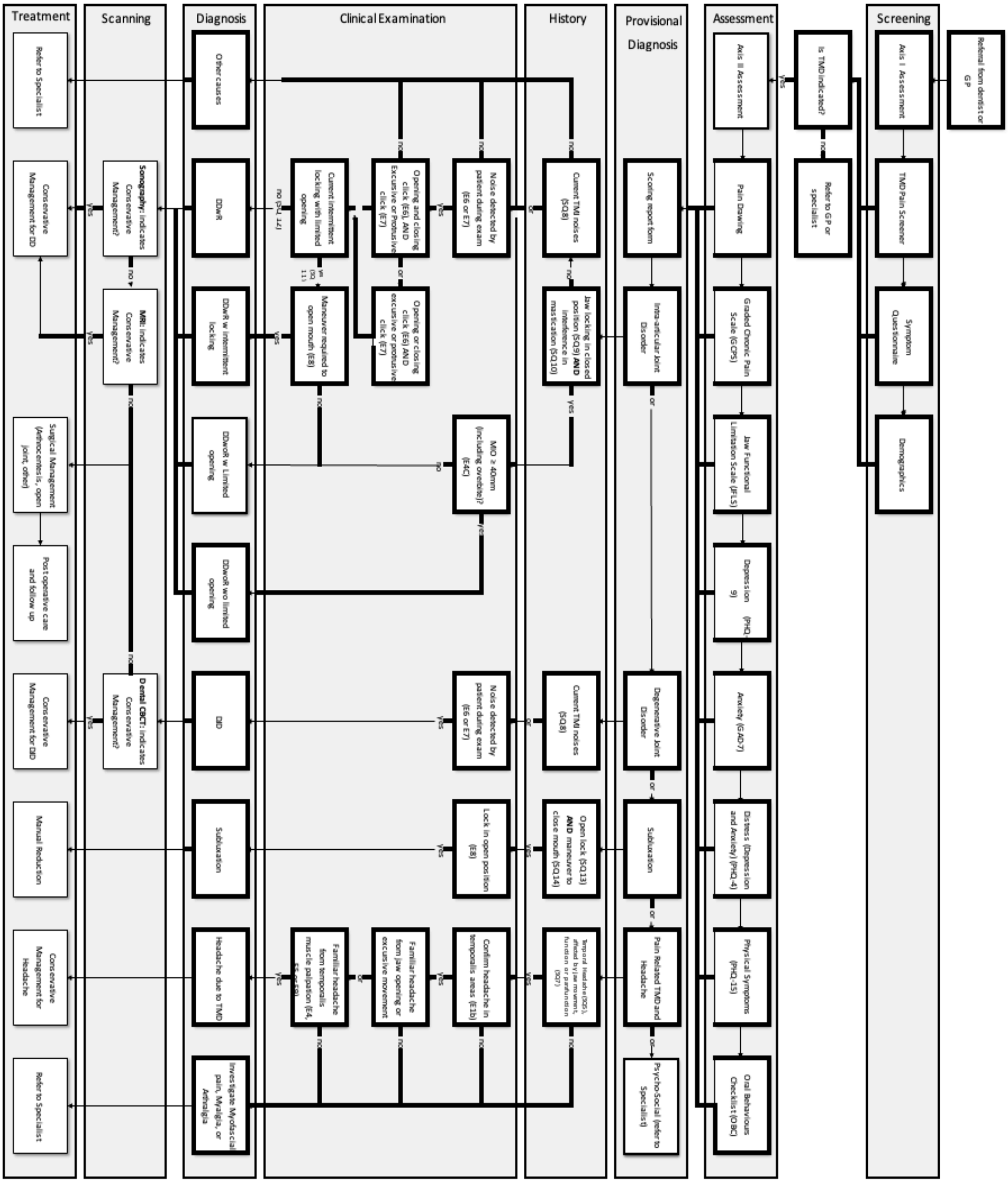
Interpretation of P values:

There is weak agreement between MRI and HHU in detecting OA, as reflected by the low odds ratio and the nominal measures. The lack of statistical significance in the Fisher's Exact Test (p = 0.237) suggests that any observed differences between MRI and HHU results could be due to chance rather than a systematic difference.

Appendix J

Flowchart and Algorithm

(see next page)


Treatment
Scanning
Diagnosis
Clinical Examination
History
Provisional Diagnosis
Assessment
Screening
Referral from dentist or GP
Axis I Assessment
TMD Pain Screener
Symptom Questionnaire
Demographics
Is TMD indicated?
Refer to GP or specialist
Axis II Assessment
Pain Drawing
Graded Chronic Pain Scale (GCPS)
Jaw Functional Limitation Scale (JFLS)
Depression (PHQ-9)
Anxiety (GAD-7)
Distress (Depression and Anxiety) (PHQ-4)
Physical Symptoms (PHQ-15)
Oral Behaviours Checklist (OBC)
Scoring report form
Intra-articular Joint Disorder
Degenerative Joint Disorder
Subluxation
Pain Related TMD and Headache
PsychoSocial (refer to Specialist)
Other causes
DDwR
DDwR w intermittent locking
DDwoR w Limited opening
DDwoR wo limited opening
DJD
Subluxation
Headache due to TMD
Investigate Myofascial pain, Myalgia, or Arthralgia
Sonography: indicates Conservative Management?
MRI: indicates Conservative Management?
Dental CBCT: indicates Conservative Management?
Refer to Specialist
Conservative Management for DD
Surgical Management (Arthrocentesis, open joint, other)
Post operative care and follow up
Conservative Management for DJD
Manual Reduction
Conservative Management for Headache
Refer to Specialist