ULTRASOUND ELASTOGRAPHY- A NOVEL TOOL IN THE ASSESSMENT OF TEMPOROMANDIBULAR DISORDERS

Abstract

Ultrasound is an essential modality within medical imaging, predominantly for assessing soft tissues. Ultrasound elastography has become commercially available in recent years for further assessment of tissues, in addition to the standard B-mode and Doppler imaging. Elastography provides a different form of tissue assessment and possibly showing pathology before it can be detected on B mode imaging. This may be of particular use in the musculoskeletal system where there is a wide spectrum of tissue specialisation. Elastography is a novel diagnostic tool and helps in evaluating the muscle stiffness both qualitatively in the form of an elastogram and quantitatively in terms of muscle elasticity index. Elastography assesses the strain (stiffness) of these tissues in response to stress, through a variety of different methods. Strain wave and Shear wave are the two techniques used in USG elastography to assess stiffness of tissues. Elastography has been used widely in musculoskeletal imaging. Temporomandibular disorders are associated with masticatory muscle pain. Till date palpation is the only subjective tool to to assess muscle pain. With the advent of elastography, it has helped in early disease detection and differential diagnosis as it reflects qualitative alterations even if morphological alterations are not noticeable. This chapter highlights the application of ultrasound elastography for various Temporomandibular disorders

Keywords: Ultrasonography, Strain wave elastography, Shear wave elastography, Temporomandibular disorders, Myofascial pain, Masseter

Authors

Dr. Deepa Jatti Patil
Professor (PhD Scholar)
Department of Oral Medicine and Radiology
K. M. Shah Dental College and Hospital
Sumandeep Vidyapeeth Deemed to be University
Gujarat, India
iafdeepa@gmail.com

Dr. Rajesh Kumar Rathore
Professor
Department Radiology,SM KS MI& RC
Sumandeep Vidyapeeth Deemed to be University
Gujarat, India
rajeshrathore26rj@gmail.com

Dr. Ashutosh Patel
Assistant Professor
Department Radiology
SBKS MI&RC
Sumandeep Vidyapeeth Deemed to be University
Gujarat, India
radioashu@gmail.com

I. INTRODUCTION

Ultrasound is a crucial modality utilised in the field of medical imaging, mostly for the evaluation of soft tissues. Various techniques, including CT, MRI, and PET, have been utilised for diagnostic imaging of morphology and function. However, the objective assessment of tissue stiffness has only recently become widely accessible with the commercial launch of ultrasound elastography. In recent times, ultrasound elastography has emerged as a supplementary tool for the comprehensive evaluation of tissues, alongside the conventional B-mode and Doppler imaging techniques. The elastic properties of tissues differ from the acoustic impedance employed in B-mode imaging and the flow properties utilised in Doppler imaging. Consequently, elastography offers a distinct means of evaluating tissues, potentially revealing pathological conditions that may not yet be detectable through B-mode imaging. This phenomenon may have significant implications within the musculoskeletal system, given the diverse range of tissue specialisation observed. Elastography is a technique used to evaluate the mechanical properties, namely the strain or stiffness, of tissues when subjected to external stress. This assessment is conducted using various methodologies.[1]

Ophir et al[2] introduced the concept of elastography as a technique for visualising the mechanical properties of living tissue in terms of strain. In the context of strain or compression elastography, the transducer applies a force, also known as stress, through repetitive manual pressure. The resulting displacement, or strain, is determined by analysing the velocities at which the tissues recover in relation to time. The qualitative assessment of tissue displacement (strain) resulting from the application of an external force (stress) is conducted.

A visual representation illustrating the distribution of elastic modulus, commonly referred to as an elastogram. The elastogram is typically represented using a color-coded scheme and is frequently overlaid onto a grayscale B mode image to facilitate anatomical localization. Quantitative measurements cannot be derived from this elastogram due to the lack of information regarding the applied force. A semi-quantitative assessment, though, can be derived by comparing the displacement of the tissue under investigation with that of a neighbouring structure, such as subcutaneous fat. Muscle elasticity index is the metric utilised for quantifying this phenomenon.[3,4]

Temporomandibular disorders (TMD) are observed in a significant proportion, ranging from 60% to 70%, of the general population.[5] However, only approximately 15% of individuals manifest symptoms associated with TMD. Among the various manifestations of TMD, myofascial pain is frequently encountered and diagnosed based on the presence of pain and tenderness upon palpation. Myofascial pain commonly manifests as localised discomfort in sensitive regions referred to as trigger points, characterised by tense bands of skeletal muscle and tendon. From a clinical perspective, it is seen that the masticatory muscle related to myofascial pain exhibits palpable hardness and stiffness.

The aetiology of myofascial pain remains incompletely elucidated despite its prevalence. The pain related to temporomandibular disorders (TMDs) results in impaired masticatory function, impacting daily activities and, notably, giving rise to psychological issues. Clinicians emphasise the need of managing the heightened rigidity and tonus of the masseter muscle as a component of the conservative management of temporomandibular disorder (TMD). Therefore, the implementation of measures aimed at preventing or mitigating temporomandibular disorders (TMD) may have a positive impact on the overall quality of life experienced by patients.[6]

The determination of the diagnosis relies on a subjective evaluation conducted by both patients and professionals, thus posing challenges in accurately assessing the ailment. Nevertheless, this observation is a subjective assessment made by skilled doctors who possess extensive expertise in the technique of palpation. There remains a lack of a comprehensive and objective evaluation of masticatory muscle stiffness in individuals suffering from myofascial pain. Hence, it is imperative to build a robust approach for the objective assessment of the degree of masticatory muscle stiffness and the impact of treatment on myofascial pain.

Several assessment measures have been employed to evaluate the stiffness associated with myofascial pain, such as Myotonometry and muscle hardness metre. However, the application of these instruments in temporomandibular disorders (TMDs) is constrained. The evaluation of modifications in masseter muscles by electromyography (EMG) has been conducted; nevertheless, it is important to acknowledge the limits of this technology. One such drawback is the susceptibility of the electrical signal to be influenced by the experimental environment.[7,8]

Ultrasonography (US) has the potential to serve as an alternate method for noninvasively visualising the morphology and thickness of the masseter and other muscles located superficially to the bone structures in the head and neck area. Elastography is an innovative diagnostic method that aids in the assessment of muscle stiffness, offering both qualitative information through elastograms and quantitative data through muscle elasticity index measurements. Previous studies conducted on different organs such as the thyroid, trapezius, and fibromyalgia have demonstrated statistically significant results.[3,4] This chapter focuses on the utilisation of ultrasound elastography in the assessment of various Temporomandibular illnesses.

II. UTILISATION OF USG ELASTOGRAPHY IN MUSCULOSKELETAL IMAGING

In recent years, there has been a notable surge in the quantity of papers pertaining to the use of USE. [9]This surge can be mostly attributed to the extensive accessibility of USE on commercial systems inside the United States. Based on a comprehensive review of the literature on the utilisation of musculoskeletal ultrasound (MSK), the European Society of Skeletal Radiology has issued a collective consensus stating that the clinical indication for the use of ultrasound is relatively limited. However, it is acknowledged as a potentially valuable technique for evaluating soft tissue masses and diagnosing nerve entrapment.[10]

There are various ways that can be utilised in the field of User Experience (UX), depending on the approach used for applying force and processing data. Strain wave elastography (StWE) and shear wave elastography (SWE) are commonly employed methodologies within the domain of musculoskeletal (MSK) radiology.[9]This chapter explores various methodologies employed in the field of elastography.

Currently, commercially available equipment employs two main categories of techniques: strain imaging and shear wave speed measurement/imaging. The different types of Elastography exhibit variations in both the approach employed to apply force (stress) and the assessment of resulting tissue displacement (strain). However, these methods can be mutually beneficial owing to their unique physical characteristics, artefacts, limitations, and specific clinical applications in which they excel.

III. THE FUNDAMENTAL TENETS OF STRAIN ELASTOGRAPHY

The fundamental idea underlying strain elastography is that the application of compression to tissue results in the generation of displacement, commonly referred to as strain. In tissues with higher stiffness, the level of strain is modest, whereas softer tissues exhibit greater levels of strain. Tissue displacement is calculated by means of a hand-held ultrasonic transducer, utilising the process of repeated physical compression. The application of modest pressure to the tissues via a transducer results in the generation of strain pictures through recurrent actions. The determination of strain involves the calculation of the axial gradient of tissue displacement between pairs of radiofrequency (RF) echo frames. In the presence of equivalent levels of stress, a rigid area undergoes a lesser degree of strain (deformation) compared to neighbouring soft tissue. By employing a colour map to depict different levels of strain magnitudes, it is possible to overlay a two-dimensional strain image with transparency over a standard B-mode image. This overlay enables the assessment of the spatial correlation between the ultrasound image and the elastography data. The elastogram visually represents the distribution of displacement, commonly shown as a color-coded graphic overlaid on the B-mode image. In general, the colour red is conventionally employed to represent softer tissue, while blue is utilised to represent tougher tissue. Tissue with intermediate elasticity, on the other hand, is commonly depicted using shades of yellow or green. (Figure 1-3) The colour coding can be adjusted to represent the varying levels of tissue stiffness. The reliability of Strain Weighted Elastography (StrWE) is further challenged by the potential distortion of elastograms caused by nonlinear variations in tissue elasticity resulting from excessive compression that is either too heavy or too light.[9,11]

Many manufacturers utilise an on-screen indicator to display the level of manual compression.[7] This indicator includes a "quality factor" which, when greater than 60, signifies the optimal compression force. Additionally, a "strain indicator" is used to determine if displacement is sufficient for calculating local strains within the region of interest (ROI).[12] Some systems offer semiquantitative tools for analysing image characteristics, such as a strain ratio.[9] This ratio serves as a measure of relative elasticity between the target ROI and the reference ROI, typically the subcutaneous fat layer. However, due to the unknown local degree of stress, it is not possible to obtain quantitative elasticity measurements in kPa. Therefore, strain elastography is a qualitative method that visually represents relative variations in tissue stiffness through sonification.[13]

IV. SHEAR WAVE ELASTOGRAPHY

Shear wave elastography is a non-invasive imaging technique used to assess the mechanical properties of tissues.Over the course of the previous ten years, SWE, which is an acronym for dynamic elastography, has been employed in both research and clinical settings to assess a range of musculoskeletal tissues. This technique enables the acquisition of qualitative and quantitative data pertaining to tissue elasticity. The technology of musculoskeletal imaging is currently undergoing rapid development, leading to the emergence of novel applications and increased therapeutic value. The utilisation of shear wave elastography (SWE) enhances the diagnostic capabilities obtained from grayscale (B-mode) ultrasound, power Doppler ultrasound, and colour Doppler ultrasound by providing quantitative measurements of the mechanical and elastic characteristics of tissue.

The shear wave is a type of transverse wave that is capable of propagating through an elastic medium when it is exposed to a periodic shear force. Shear is a phenomenon characterised by the alteration in the shape of a layer of substance, while its volume remains constant. This alteration is caused by a pair of opposing forces of equal magnitude operating along the two sides of the layer. Following the shear interaction, the first layer (referred to as tissue) will revert to its original configuration, but the neighbouring layers experience shear and incur additional displacement as the shear wave propagates as a transverse shear wave.[14]

V. THE FUNDAMENTAL TENETS OF SHEAR WAVE ELASTOGRAPHY

The initial phase involves the generation of shear waves with the application of focused acoustic radiation force from a linear ultrasound array. This process induces localised stress and displacement inside the tissue.

During the initial phase, the shear waves that are produced propagate through the surrounding tissues in a transverse plane, which is perpendicular to the primary wave responsible for generating the acoustic radiation force. These shear waves travel at a considerably reduced velocity and result in displacements of the tissue in a shearing manner.

In the second step, a rapid plane wave excitation technique is utilised to observe the displacement of tissue and measure the velocities of shear waves throughout their propagation. The process of determining tissue displacement by the utilisation of a speckle tracking algorithm. In the third phase, tissue displacement maps are employed to ascertain the shear-wave velocity (cs), a parameter commonly denoted in metres per second. The relationship between the shear-wave velocities observed at each pixel and the shear modulus G may be described as a direct proportionality. The shear modulus G, which characterises the stiffness and elasticity of the tissue, is computed by a straightforward mathematical equation. The resulting values are commonly expressed in kilopascals, a unit of pressure. The shear modulus is a fundamental property of materials that quantifies the relationship between stress and strain. It is mathematically expressed as G = rcs^2, where G represents the shear modulus, r denotes the density of the material, c represents the speed of shear waves, and s represents the shear wave frequency. The equation E = 3G represents the formal definition of the Young modulus (E) for isotropic media. The determination of material density for soft tissue is commonly derived from values reported in relevant literature pertaining to the specific tissue under investigation, or by approximating the density of water (1 g/cm3) (36,37). The relationship between the shear modulus (G) and Young's modulus (E) has been observed in many examinations, with some studies reporting the equation E = 2G(1+), where indicates the Poisson ratio. The equation E = 3G is occasionally employed to convert the shear modulus (G) to the Young's modulus (E) for incompressible materials, on the assumption that soft tissues with moderate deformations exhibit incompressibility (i.e., = 0.5)

(39). As a result, it is worth noting that while several research make reference to shear-wave values or G, others provide information on E using this correlation.

In the context of the United States screen, visual representations of quantitative shear modulus maps are shown by a color-coded elasto-gram. These maps depict shear-wave velocities in units of metres per second (as seen in Figures 2) or tissue elasticity measured in kilopascals. In general, it is seen that red elastograms are indicative of a firm consistency, while blue elastograms suggest a soft consistency. On the other hand, green and yellow elastograms are associated with an intermediate level of stiffness (Figure 4).[15,16]

The phenomenon of tissue shear deformation propagating as a shearwave is a fundamental premise employed in the field of Shear Wave Elastography (SWE). SWE is a type of dynamic elastography that relies on measuring the distribution of tissue propagation velocities for shear waves created by ultrasonic pulses. Software engineering (SWE) has the capability to quantitatively measure the absolute elasticity value of a structure that has been photographed. In addition, SWE can also provide qualitative depictions of the structure through the use of elastograms. It has been shown that shear waves exhibit a higher velocity when propagating through tissues with greater density. The quantitative measurement can be represented by the shear wave velocity in metres per second (m/s) or by the tissue elasticity determined through the calculation of the shear modulus in kilopascals (kPa).[4]

VI. DISCUSSION

Numerous research has been undertaken to evaluate the stiffness of the masseter muscle using strain and shear wave elastography techniques. In their study, Ariji Y et al.[17] examined the correlation between the elasticity index ratio of the masseter muscle, as determined through sonographic elastography, and the hardness measurements obtained using a hardness metre in a group of healthy individuals. Additionally, they aimed to elucidate the specific characteristics of masseter muscle hardness in patients with temporomandibular disorder (TMD) who experience myofascial pain. The acquisition of sonographic elastography pictures was conducted utilising a LOGIQ E9 ultrasound system manufactured by GE Healthcare. Subsequently, the MEI ratios were computed by employing the Elasto Q programme. This study aimed to investigate the correlation between the Masseter Enlargement Index (MEI) ratio and the hardness of the masseter muscle, as determined by a hardness metre. The study sample consisted of 35 individuals who were in good health. A comparison was made between the MEI ratio in a group of 8 patients with myofascial pain associated with temporomandibular disorders (TMD) and that of a control group consisting of healthy volunteers. There was a substantial correlation observed between the MEI ratio and the hardness of the masseter muscle. A notable disparity was seen in the MEI ratios between the symptomatic and asymptomatic sides among patients with temporomandibular disorder (TMD) experiencing myofascial pain. The maxillary expansion index (MEI) ratio on the symptomatic side in individuals with temporomandibular disorder (TMD) was found to be greater than the MEI ratio on the right side in a control group of healthy volunteers. The researchers reached the conclusion that Sonographic elastography is a viable method for quantifying muscle stiffness. This method can be chosen to visually represent the characteristics of painful muscles.

The study conducted by Ariji Y et al.[18] (2018) aimed to examine the alterations in intramuscular characteristics using sonographic elastography (SE) during low-level static contraction of the masseter muscle. The objective was to elucidate the association between these changes and the overall hardness and presence of edoema. A group of ten individuals who were in good health participated in a study where they engaged in sustained bilateral biting at a level of 20% of their maximum voluntary contraction for a duration of 10 minutes. The scans of the masseter muscles using SE and magnetic resonance (MR) imaging techniques were conducted prior to, immediately following, and 10 minutes subsequent to the exercise session. The evaluation of the masseter muscle elasticity index (MEI) ratio, muscle thickness, and distribution of intramuscular soft and hard areas was conducted using SE images. The measurement of the signal to noise ratio (SNR), which serves as an indicator of the water content, was conducted using magnetic resonance (MR) images. The soft area ratio exhibited statistically significant associations with the water content, as indicated by the signal-to-noise ratio (SNR). The ratio of the difficult region

Demonstrated noteworthy associations were observed between the overall muscle hardness, as indicated by the MEI ratio. The researchers reached the conclusion that both clinical and experimental applications can utilise intramuscular soft and hard zones.

In their study, Nakayama et al.19 conducted an investigation into the elasticity index (EI) ratios of the masseter muscles in healthy volunteers. They employed a single coupling agent as a reference to verify its utility in obtaining these ratios. The study involved the examination of muscle phantoms possessing predetermined elasticity values (20, 40, and 60 kPa in terms of Young's modulus) through the utilisation of strain-type sonoelastography. A coupling agent was employed as the reference during the examination process. The study involved the determination of correlation coefficients between the EI ratio and Young's modulus of muscle phantoms. Significant correlations were observed between the ratios of elastic indentation (EI) and Young's modulus, for both soft and hard reference materials. The magnitudes of the EI ratios exhibited greater variability in the presence of soft coupling agents compared to hard coupling agents, and this variability was seen to be more pronounced in phantoms with an elasticity of 60 kPa. No significant variations were observed in the EI ratios of the masseter muscle at rest when comparing males and females, as well as the right and left sides. The ratio exhibited an increase during the act of clenching. The researchers reached the conclusion that the hard reference coupling agent was appropriate for achieving the EI ratio of the masseter muscle.

Habibi et al.[20] (2020) did a study with the aim of establishing normative quantitative elasticity values for the disc and masseter muscle. These values might serve as a reference point for future investigations in this area. The mean stiffness values of the disc in the anterior section were 37.02 ± 23.75 kPa and 3.28 ± 1.09 m/s. In the intermediate part, the mean stiffness values were 30.47 ± 18.89 kPa and 2.97 ± 1.04 m/s. Lastly, in the posterior part, the mean stiffness values were 22.61 ± 13.97 kPa and 2.55 ± 0.88 m/s. The stiffness values exhibited a statistically significant decrease in the posterior region of the disc when compared to the remaining portions, for both male and female subjects. There were no statistically significant variations observed in the average stiffness measurements of the masseter muscle in relation to mouth position, age, or gender. The present work has presented normative quantitative elasticity values for the disc and masseter muscle, which can serve as a valuable reference for future investigations. The elasticity values of the disc exhibit higher values in women as compared to men. This could perhaps be one of the factors contributing to the higher prevalence of temporomandibular disorder (TMD) in women. The rigidity of the temporomandibular joint (TMJ) disc was found to be substantially lower in the posterior region. Shear wave elastography (SWE) is a valuable imaging technique that can be employed alongside conventional ultrasonography to assess the temporomandibular joint (TMJ) disc and masticatory muscles.

In their study, Paluch et al.[21] (2021) examined the efficacy of shear wave elastography in assessing the stiffness of the temporomandibular disc among individuals diagnosed with temporomandibular disorders (TMDs). The research comprised a sample of 37 individuals diagnosed with proven temporomandibular disorders (TMDs) and 208 individuals who were deemed to be in good health. The study found that patients exhibited a notable increase in stiffness in the intermediate zone of the disc (specifically, region of interest [ROI] 1), while experiencing a significant decrease in stiffness in the anteriorly displaced area of the disc (ROI 3). The results of a receiver operating characteristics (ROC) study demonstrated that a stiffness reduction of less than 8.667 KPa in region of interest (ROI) 3 yielded a sensitivity of 100%, specificity of 97.3%, positive predictive value (PPV) of 100%, and negative predictive value (NPV) of 99.5% in differentiating between individuals with temporomandibular disorders (TMDs) and those without. While an augmentation in the stiffness of ROI 1 to a minimum of 54.33 KPa demonstrated notable specificity and negative predictive value (NPV), the sensitivity and positive predictive value (PPV) of this predictor were found to be zero. The results of the study indicate that a reduction in stiffness of the anteriorly dislocated disc below 8.667 kPa can effectively serve as a reliable indicator for identifying individuals with temporomandibular disorders (TMDs). Patients diagnosed with temporomandibular disorders (TMDs) may experience a steady decline in the elasticity of their articular discs. The evaluation of this particular characteristic using shear wave elastography (SWE) has the potential to serve as an indicator of pathological changes occurring in the temporomandibular joints (TMJs).

A Prospective research was undertaken by Olchowy et al.[22] with a sample of 35 patients diagnosed with masticatory muscle problems. The duration of the study spanned a period of eight weeks. The individuals undergoing treatment received manual therapy and stabilisation occlusal splint interventions. Their progress was assessed through the utilisation of shear wave elastography to monitor the masseter muscles, as well as patient-reported outcome measures to evaluate pain levels, anxiety levels, sleep quality, overall life satisfaction, and perceived stress levels. Following the intervention, there was a notable reduction in the rigidity of both masseter muscles, with a statistically significant decrease of 4.21 kilopascals. The participants indicated a noteworthy decrease in discomfort. Initially, the median scores exhibited a range of 5 to 8. However, following the implementation of the treatment, the range of scores decreased to 0 to 1, with statistical significance shown by a p-value of less than 0.0001. The patients also experienced notable enhancements in relation to all indicators of outcomes as stated by the patients themselves. The researchers reached the conclusion that shear wave elastography exhibits considerable potential for widespread utilisation in clinical settings to assess the efficacy of treatment for masticatory muscle problems. This is primarily attributed to its objective nature and non-invasive properties.

Toker et al.[23] did a study aimed at assessing the utility of Shear wave elastography in the context of bruxism. Surface electromyography (SWE) was conducted on both the left and right masseter muscles in three distinct conditions: when the jaw was in a relaxed state, when the jaw exerted 50% of the subjective maximal biting force, and when the jaw was maximally opened. During periods of relaxed jaw, the surface wave velocity (SWE) exhibited a notable increase in individuals with bruxism (1.92 m/s ± 0.44) compared to the control group (1.66 m/s ± 0.24). The findings of the study indicate that the utilisation of SWE in bruxism demonstrates feasibility and holds potential for diagnostic and monitoring purposes in relation to the condition.

The aforementioned studies provide support for the utilisation of ultrasound elastography (USG elastography) in the early detection of diseases and differential diagnosis, as it has the potential to identify qualitative changes even in the absence of evident morphological changes. Shear wave elastography is considered to be more advantageous compared to strain wave elastography due to its ability to provide a quantitative assessment of muscle and disc stiffness, while also minimising the influence of operator variability.

VII. APPLICATIONS OF USG ELASTOGRAPHY IN TMDS

1. Assessing the stiffness of masseter muscles in conditions of Myofascial pain in TMDs
2. Assessing the normal values of stiffness of masseter muscles in healthy adults and children
3. Assessing the normal values of stiffness of articular disc of temporomandibular joint in patients with internal disc derangement and healthy adults.
4. Used as diagnostic tool to assess the decrease in muscle stiffness before and after treatment in patients with myofascial pain
5. Can be used a potential tool to assess patients with bruxism and as a follow up modality after treatment in these patients

VIII. CONCLUSION

USG elastography is a cost-effective diagnostic modality that has the additional benefit of employing non-ionizing radiation. This modality is a real-time imaging technique that yields prompt results within a brief timeframe. As delineated in the aforementioned research, USG Elastography exhibits potential as a viable modality for evaluating the stiffness of the masseter muscle and temporomandibular joint disc. However, it is crucial to note that the existing body of evidence remains inadequate in establishing conclusive findings. Further research is required to ascertain the efficacy of elastography in the characterization of temporomandibular disorders, particularly through the examination of larger sample sizes.

IX. ACKNOWLEDGEMENT

This chapter is part of PhD research project -SVIEC/ON/MEDI/PhD/22011

Conflict of Interest: NIL

Funds: Nil

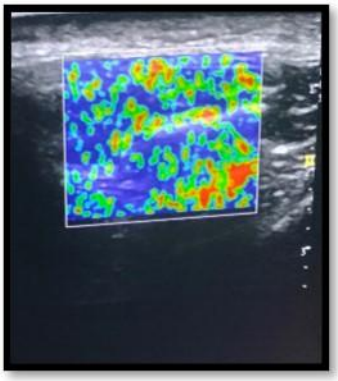

Figure 1: Color coded elastogram -blue areas depicting areas of muscle hardness

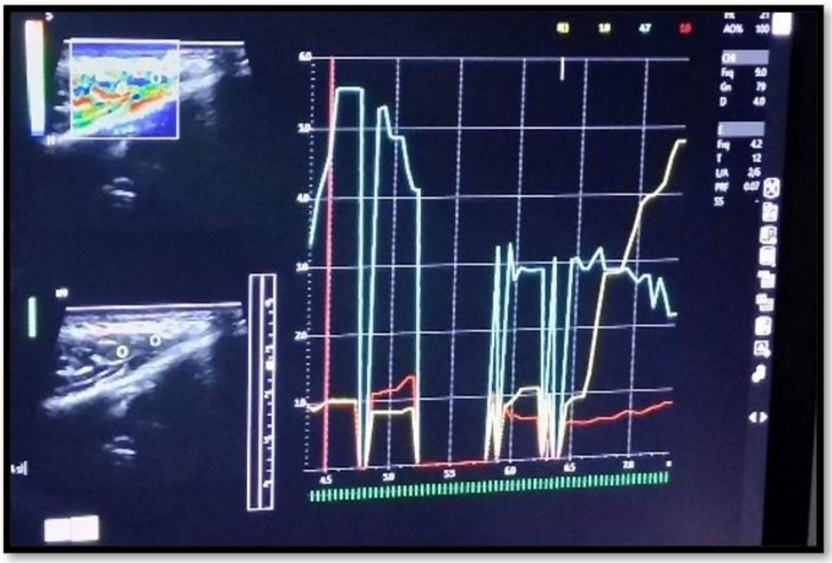

Figure 2: Masseter muscle elasticity index Ratio of elasticity index of muscle to subcutaneous tissue in patients with myofascial pain

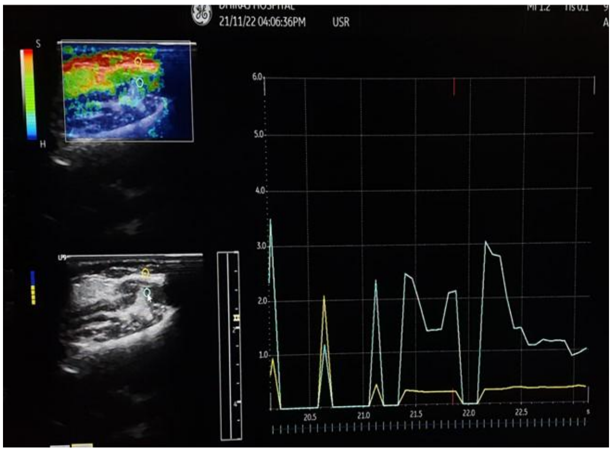

Figure 3: Masseter muscle elasticity index Ratio of elasticity index of muscle to subcutaneous tissue in healthy patients

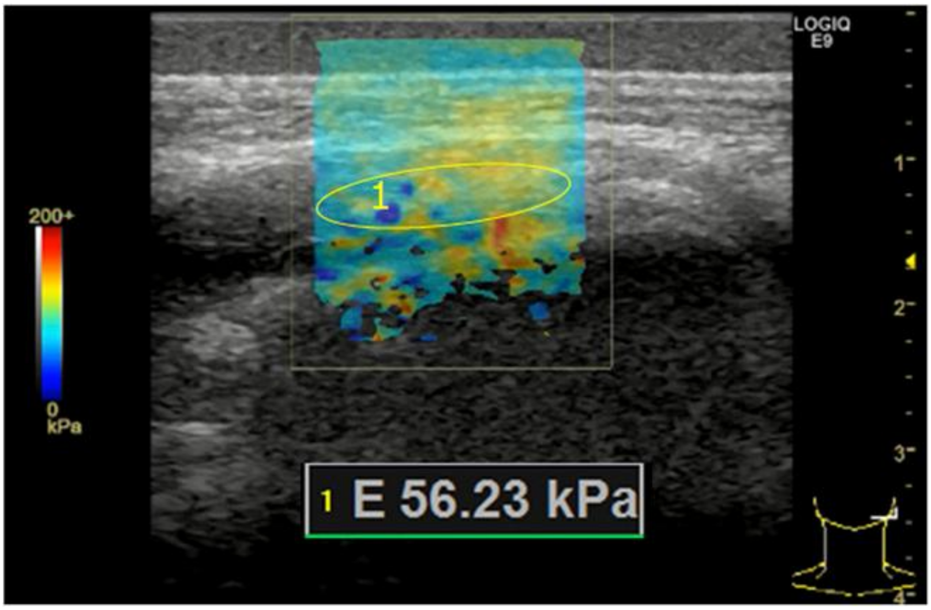

Figure 4: Shear wave elastogram of Masseter. The region of interest iss set on the masseter muscle, and Young's modulus of the masseter muscle was measured (56.23 kPa)

REFERENCES

[1] Winn N, Lalam R, Cassar-Pullicino V. Sonoelastography in the musculoskeletal system: Current role and future directions. World J Radiol. 2016 28;8(11):868-879.
[2] Ophir J, Alam SK, Garra BS, Kallel F, Konofagou EE, Krouskop T, et al. Elastography: Imaging the elastic properties of soft tissues with ultrasound. J Med Ultrason (2001). 2002;29(4):155
[3] Gennisson JL, Deffieux T, Fink M, Tanter M. Ultrasound elastography:principles and techniques. Diagn Interv Imaging 2013; 94:487-495.
[4] Drakonaki EE, Allen GM, Wilson DJ. Ultrasound elastography for musculoskeletal applications. Br J Radiol 2012; 85: 1435-1445.
[5] Dworkin SF, LeResche L. Research diagnostic criteria for temporomandibular disorders: review, criteria, examinations and specifications, critique. *J Craniomandib Disord.* 1992;6(4):301–355.
[6] Poluha RL, Grossmann E, Iwaki LCV, Uchimura TT, Santana RG, Iwaki Filho L. Myofascial trigger points in patients with temporomandibular joint disc displacement with reduction: a cross-sectional study. J Appl Oral Sci. 2018;26: e20170578
[7] Yu JF, Chang TT, Zhang ZJ. The Reliability of Myoton PRO in Assessing Masseter Muscle Stiffness and the Effect of Muscle Contraction. Med Sci Monit. 2020;26: e926578.
[8] Hiraiwa Y, Ariji Y, Kise Y, Sakuma S, Kurita K, Ariji E. Efficacy of massage treatment technique in masseter muscle hardness: robotic experimental approach. Cranio. 2013;31(4):291-9.
[9] Bamber J, Cosgrove D, Dietrich CF, et al. EFSUMB guidelines and recommendations on the clinical use of ultrasound elastography. Part 1: Basic principles and technology. Ultraschall Med 2013;34 (02):169–184.
[10] Sconfienza LM, Albano D, Allen G, et al. Clinical indications for musculoskeletal ultrasound updated in 2017 by European Society of Musculoskeletal Radiology (ESSR) consensus. Eur Radiol 2018;28(12):5338–535.
[11] Klauser AS, Miyamoto H, Bellmann-Weiler R, FeuchtnerGM,Wick MC, Jaschke WR. Sonoelastography: musculoskeletal applications. Radiology 2014;272(03):622–633.
[12] Wu CH, Chen WS, Park GY, Wang TG, Lew HL. Musculoskeletal sonoelastography: a focused review of its diagnostic applications for evaluating tendons and fascia. JMedUltrasound 2012;20:79–86.
[13] Snoj Ž, Wu CH, Taljanovic MS, Dumić-Čule I, Drakonaki EE, Klauser AS. Ultrasound Elastography in Musculoskeletal Radiology: Past, Present, and Future. Semin Musculoskelet Radiol. 2020 Apr;24(2):156-166.

[14] Taljanovic MS, Gimber LH, Becker GW, Latt LD, Klauser AS, Melville DM, Gao L, Witte RS. Shear-Wave Elastography: Basic Physics and Musculoskeletal Applications. Radiographics. 2017;37(3):855-870.
[15] Taljanovic MS, Melville DM, Klauser AS, et al. Advances in lower extremity ultrasound. Curr Radiol Rep 2015;3(6):19.
[16] Bercoff J, Tanter M, Fink M. Supersonic shear imaging: a new technique for soft tissue elasticity mapping. IEEE Trans Ultrason Ferroelectr Freq Control 2004;51(4):396–409.
[17] Ariji, Y., Gotoh, A., Hiraiwa, Y. et al. Sonographic elastography for evaluation of masseter muscle hardness. Oral Radiol 2013; 29:64–69.
[18] Ariji Y, Nakayama M, Taguchi A, Gotoh A, Kise Y, Katsumata A, Kurita K, Ariji E. Intramuscular changes of soft and hard areas after low-level static contraction of the masseter muscle and the correlations with muscle hardness and increase in water content: evaluations with sonographic elastography and magnetic resonance imaging. Oral Surg Oral Med Oral Pathol Oral Radiol. 2013 ;116(3):354-61.
[19] Nakayama M, Ariji Y, Nishiyama W, Ariji E. Evaluation of the masseter muscle elasticity with the use of acoustic coupling agents as references in strain sonoelastography. Dentomaxillofac Radiol. 2015;44(3):20140258.
[20] Paluch Ł, Maj P, Pietruski P, Korba M, Noszczyk BH. Shear Wave Elastography in the Evaluation of Temporomandibular Joint Disorders. Ultrasound Med Biol. 2020; 46:46-54.
[21] Habibi HA, Ozturk M, Caliskan E, Turan M. Quantitative assessment of temporomandibular disc and masseter muscle with shear wave elastography. Oral Radiol. 2022; 38:49-56
[22] Olchowy A, Seweryn P, Olchowy C, Wieckiewicz M. Assessment of the masseter stiffness in patients during conservative therapy for masticatory muscle disorders with shear wave elastography. BMC Musculoskelet Disord. 2020;23(1):439.
[23] Toker C, Marquetand J, Symmank J, Wahl E, Huettig F, Grimm A, Kleiser B, Jacobs C, Hennig CL. Shear Wave Elastography in Bruxism-Not Yet Ready for Clinical Routine. Diagnostics (Basel). 2023;13(2):276.