Dossier Temporomandibular Disorders, Orofacial Pain, Bruxism, and Sleep Apnea

Simultaneous Audio Recording and Magnetic Resonance Imaging of the Temporomandibular Joint *

Grabación de audio e imágenes de resonancia magnética simultáneas de la articulación temporomandibular

Gravação simultânea de áudio e ressonância magnética da articulação temporomandibular

DOI : https://doi.org/10.11144/Javeriana.uo42.sarm
Submission Date: 16 August 2023
Acceptance Date: 26 December 2023
Publication Date: 31 December 2023

Yoav Nudell [a]
Good Samaritan University Hospital. New York, USA.
ynudell@gmail.com
https://orcid.org/0000-0002-9140-7599

Juliana Gomez [a]
Ascension Macomb-Oakland Hospital. New York, USA.
Juliana.gomez.dds@gmail.com
https://orcid.org/0000-0001-6805-955X

Elizabeth F. Vaynblat [a]
Brookdale University Hospital and Medical Center. New York, USA.
efv211@nyu.edu
https://orcid.org/0000-0003-1001-0336

Mari Hagiwara [a]
New York University Langone Health. New York, USA.
Mari.Hagiwara@nyulangone.org
https://orcid.org/0000-0002-3715-5159

Robert S. Glickman [a]
New York University College of Dentistry. New York, USA.
rsg1@nyu.edu
https://orcid.org/0000-0003-0168-4582

Authors' Note: [a] **Correspondence:** ynudell@gmail.com; Juliana.gomez.dds@gmail.com; efv211@nyu.edu; Mari.Hagiwara@nyulangone.org

ABSTRACT

Background: Temporomandibular joint disorder is a complex disease requiring multimodal treatment and often a delayed diagnosis. Purpose: The primary objective of this study is to evaluate the feasibility of simultaneously recording joint sounds while obtaining 3-tesla cine-magnetic resonance imaging (3T cine-MRI) of the temporomandibular joint (TMJ). A secondary objective pertains to optimization of a dynamic TMJ imaging protocol to maximize image quality and speed while maintaining synchronicity. **Methods:** Investigators enrolled four subjects (August 2018 to August 2019) eliciting audible joint sounds during continuous open-close jaw movements during clinical evaluation at the New York University College of Dentistry. A contact fiber-optic microphone (OptiRhythm 4130, Optoacoustics, Yehuda Israel) was utilized to record joint sounds elicited with functional movements during MR dynamic imaging at NYU Langone Health and all data was recorded appropriately. **Results:** Results of this feasibility study demonstrate the successful integration of audio and 3-Tesla MR imaging for the TMJ in all subjects. This protocol was shown to be well-tolerated by the subjects. A precise correlation of

the movement of TMJ structures within cine-MRI images and with audible observations was achieved and assessed by an experienced oral and maxillofacial surgeon and an experienced radiologist. **Conclusion:** This protocol for simultaneous audio/cine-MRI is a viable tool for studying TMJ health and disease. In future studies, we anticipate this protocol will ultimately refine our understanding of TMJ sounds and their relation to anatomy, physiology, and pathology. In addition, we hope to establish a diagnostic aid to guide surgical and non-surgical decision-making more precisely.
Keywords: audio recording; dentistry; diagnostics; magnetic resonance imaging; oral surgery; temporomandibular disorders; temporomandibular joint; temporomandibular joint disorders

RESUMEN

Antecedentes: el trastorno de la articulación temporomandibular es una enfermedad compleja que requiere tratamiento multimodal y, a menudo, un diagnóstico tardío**. Objetivo:** el objetivo principal de este estudio es evaluar la viabilidad de grabar simultáneamente sonidos articulares mientras se obtienen imágenes de resonancia magnética cinematográfica de 3 teslas (cine-MRI 3T) de la articulación temporomandibular (ATM). Un objetivo secundario se refiere a la optimización de un protocolo dinámico de imágenes de la ATM para maximizar la calidad y la velocidad de la imagen manteniendo la sincronicidad. **Métodos:** Los investigadores inscribieron a cuatro sujetos (de agosto de 2018 a agosto de 2019) que provocaron sonidos articulares audibles durante los movimientos continuos de apertura y cierre de la mandíbula durante la evaluación clínica en la Facultad de Odontología de la Universidad de Nueva York. Se utilizó un micrófono de fibra óptica de contacto (OptiRhythm 4130, Optoacoustics, Yehuda Israel) para registrar los sonidos articulares provocados con movimientos funcionales durante la resonancia magnética dinámica en NYU Langone Health y todos los datos se registraron de manera adecuada. **Resultados:** Los resultados de este estudio de viabilidad demuestran la integración exitosa del audio y las imágenes de resonancia magnética de 3 Tesla para la ATM en todos los sujetos. Se demostró que este protocolo era bien tolerado por los sujetos. Un cirujano oral y maxilofacial experimentado y un radiólogo experimentado lograron y evaluaron una correlación precisa del movimiento de las estructuras de la ATM dentro de las imágenes de cine-MRI y con observaciones audibles. **Conclusión:** Este protocolo para audio/cine-MRI simultáneo es una herramienta viable para estudiar la salud y la enfermedad de la ATM. En estudios futuros, anticipamos que este protocolo finalmente perfeccionará nuestra comprensión de los sonidos de la ATM y su relación con la anatomía, fisiología y patología. Además, esperamos establecer una ayuda diagnóstica para guiar con mayor precisión la toma de decisiones quirúrgicas y no quirúrgicas.
Palabras clave: articulación temporomandibular; cirugía oral; diagnóstico; grabación de audio; imagen de resonancia magnética; odontología; trastornos de la articulación temporomandibular; trastornos temporomandibulares

RESUMO

Antecedentes: A disfunção da articulação temporomandibular é uma doença complexa que requer tratamento multimodal e muitas vezes um diagnóstico tardio. **Objetivo:** O objetivo principal deste estudo é avaliar a viabilidade de gravação simultânea de sons articulares durante a obtenção de ressonância magnética de 3 tesla (cine-MRI 3T) da articulação temporomandibular (ATM). Um objetivo secundário refere-se à otimização de um protocolo de imagem dinâmico da ATM para maximizar a qualidade e velocidade da imagem, mantendo a sincronicidade. **Métodos:** Os investigadores inscreveram quatro indivíduos (agosto de 2018 a agosto de 2019) que eliciaram sons articulares audíveis durante movimentos contínuos de abertura e fechamento da mandíbula durante avaliação clínica na Faculdade de Odontologia da Universidade de Nova York. Um microfone de fibra óptica de contato (OptiRhythm 4130, Optoacoustics, Yehuda Israel) foi utilizado para registrar sons articulares provocados com movimentos funcionais durante imagens dinâmicas de RM na NYU Langone Health e todos os dados foram registrados adequadamente. **Resultados:** Os resultados deste estudo de viabilidade demonstram a integração bem-sucedida de imagens de áudio e RM de 3 Tesla para a ATM em todos os indivíduos. Este protocolo mostrou-se bem tolerado pelos sujeitos. Uma correlação precisa do movimento das estruturas da ATM nas imagens de cine-RM e com observações audíveis foi alcançada e avaliada por um cirurgião oral e maxilofacial experiente e um radiologista experiente. **Conclusão:** Este protocolo para áudio/cine-RM simultâneo é uma ferramenta viável para estudar a saúde e a doença da ATM. Em estudos futuros, prevemos que este protocolo acabará por refinar nossa compreensão dos sons da ATM e sua relação com a anatomia, fisiologia e patologia. Além disso, esperamos estabelecer um auxílio diagnóstico para orientar com mais precisão a tomada de decisões cirúrgicas e não cirúrgicas.
Palavras-chave: articulação temporomandibular; cirurgia oral; diagnóstico; distúrbios da articulação temporomandibular; distúrbios temporomandibulares; gravação de áudio; imagem de ressonância magnétic; odontologia

INTRODUCTION

Temporomandibular joint disorders (TMD) regularly involve complex interactions between many anatomic and physiologic factors. A diverse array of disease etiologies and reparative processes contribute to the clinical manifestations of TMD. Affected components of the temporomandibular joint (TMJ) apparatus underlying joint dysfunction and the consequent clinical manifestations include but are not limited to the muscles of mastication and TMJ-associated hard and soft tissues. TMJ disorders are characterized as either intra- or extra-articular, involving complex interactions between many anatomic structures including the joint proper, muscles of mastication and other accompanying hard and soft tissues. They are debilitating when severe, presenting with sounds, tenderness, stiffness, locking and decreased range of motion, among others. Intra-articular TMD is not exclusively a clinical diagnosis, necessitating clinical examination alongside diagnostic imaging that even then may result inconclusively (1-8). This leads to investigation into the following question---how can evaluation and diagnosis of a pathologic joint be optimized to ultimately address a debilitating disease process that affects a multitude of individuals?

Interestingly, the TMJ elicits sounds in both healthy and disease states. Internal derangements of TMJ may present in a variety of ways often with specific and reproducible joint sound. These TMJ sounds have been described and quantified with an array of methodologies. Both imaging and sound data have been used to evaluate symptomatic joints and aid in diagnosis of temporomandibular joint disorder (1-4). Combining these variables introduces the potential for a multi-modal clinical tool. We propose that a mechanistic understanding of TMJ sound generation and recording alongside imaging can lead to a better understanding of disease states, and consequently, more informed TMD diagnoses and individualized treatments (3,4).

Magnetic resonance imaging (MRI) is the imaging modality of choice for detecting internal derangements (ID), including disc position and osseous changes in the TMJ, thus facilitating characterization of intra-articular dysfunction and ultimately, pre-surgical planning (9,10). MRI provides optimal visualization of masticatory muscles, ligaments, cartilaginous disc of the TMJ, while computed tomography (CT) imaging can better assess hard tissue pathology (5,7). A typical diagnostic TMJ series consists of open and closed mouth stills demonstrating joint and disc position at different points during function. Some will obtain dynamic imaging of the joint which, while more time consuming and technique-sensitive, is most effective in demonstrating the physiologic movement of the joint as well as the changing position of the condyle and the articular disc in real time (10-13).

Simultaneous recording of joint sounds and cine-MRI (AC-MRI) of the TMJ has never been achieved, despite TMJ sound having been assessed by an array of methodologies, including clinical symptoms, recorded wave forms and intra-operative presentation. Audible TMJ sounds exist in a number of individuals (31-42 %); and such joint sounds may be an indication of abnormalities within the joint capsule and may present coincident with pain and pathologic conditions or indicate a functional adaptation independent of pain and discomfort (14,15). Differing vibrations generated by the physical state of a joint translate to audible sounds that may be measured in decibels. Diagnostic capability of TMJ sounds has been subject to controversy due to clinical and diagnostic applicability. Furthermore, there is no current consensus revealing the anatomic or functional source of sound production in the TMJ (14-17). The evidence that exists regarding TMJ function and pathologic variation was gathered historically from ex vivo, hemi-dissected, or surgically altered specimens (3,6-8,10). Over 700 joints were assessed to create the Wilkes classification, which includes joint sounds---clicking, popping, crepitus---as features exhibited through a spectrum of healthy to severely diseased joints (8).

Audio recording of the TMJ while obtaining cine-MRI imaging may provide a multi-modal tool to correlate these sounds with the anatomy, physiology, and pathology of the TMJ. The current understanding is that the physical manifestation of TMJ sounds has been attributed to sliding of articular surfaces, stick-slip friction, impact of osseous structures against each other, and synovial cavitation

(16,17). While these sounds have not been correlated to MRI imaging in the TMJ, dissolved gases in fluid motion resulting from synovial cavitation have been visualized on MRI in other joints. Thus, our aim is to combine two diagnostic modalities, audio and cine-MRI, to establish a reproducible protocol for thorough analysis of the TMJ. Additionally, we hope to optimize the dynamic TMJ imaging protocol to maximize image quality and speed (17-20).

MATERIALS AND METHODS

After obtaining approval from the New York University School of Medicine Institutional Review Board (IRB #i16-00043), four volunteers with audible temporomandibular joint sounds during open-close jaw movements, were enrolled in this pilot study of a clinical trial. All subjects were screened and informed of the aims of this work to analyze the feasibility of the study methods. Inclusion criteria for the subjects were: individuals identified by an investigator to have a reproducible joint sound during clinical exam, aged 21 or older, capable of providing informed consent, and able to attend all scheduled study visits. Subjects who had a history of claustrophobia, who were pregnant or had significant comorbid medical conditions complicating interpretation of data were excluded. Potential subjects with clinical signs of mechanical joint abnormalities including abnormal range of motion, locking, or muscle weakness were excluded.

The study design included two encounters: During the first visit consent was obtained, a TMJ exam was performed, and inclusion/exclusion criteria were assessed. The clinical exam was performed at New York University dentistry clinics. During the second visit, dynamic MRI and sound recordings were obtained. The basic AC-MRI recording setup can be found in Figure 1. A fiber-optic microphone (FOM) (OptiRhythm, Optoacoustics, Yehuda Israel), Figure 1b,1c, was used to record joint sounds during high-speed cine 3.0-T MRI scan at NYU Langone Health, Figure 1a. The FOM is a contact microphone, weighs 18.0 g, sensitivity at 1 mg of 10 mV, equivalent self-noise $\leq$ 2 µg and has a frequency response of +/-3 dB over the range of 10 to 200 Hz. Real-time dynamic MRI functions by acquiring rapid gradient echo sequences with a significant reduction of the repetition time responsible for a residual transverse magnetization before the next radiofrequency pulse. These sequences have high temporal resolution, which therefore allows acquisition of an image---in this case the entire joint; in a few hundred milliseconds and fast repetition of image slices. The entire sequence of images acquires the joint in 3-5 seconds before then repeating the process to acquire more sets of imaging. There is no repetition required, however, allowing this process to run far more quickly than a standard or static MRI once the image acquisition begins (11,13).

The FOM was placed in the area of interest (Figure 1c) and was secured with self-adherent wrap and surgical tape. The patient was positioned for MRI image acquisition in the scanner. As the dynamic MRI scan was initiated, all subjects were instructed to open to maximum incisal opening over the span of approximately 3 to 5 seconds and then to close fully to baseline occlusion over the span of 3 to 5 seconds. The MRI acquisition was then stopped, and the patient was instructed to remain supine in the scanner until images were evaluated for quality and positioning by the neuroradiologist present. Patients tolerated the protocol well.

An experienced neuroradiologist designed, optimized and implemented multiple MRI scanning protocols, and reviewed all MRI imaging once obtained to establish a radiologic diagnosis for all patients. A variety of techniques were incorporated to optimize the temporal and image resolution. Achieving a frame rate of approximately 5 - 10 frames per second. Using the Horos medical image viewer v3.3.6, DICOM images from each cine-MRI scan were converted into still images and exported in a movie format. Audacity 2.1.2 was used for audio acquisition. Once the audio data was saved in Audacity, Adobe Audition 13.0.10.32 program was used for audio processing, ambient noise filtration and signal amplification.

Adobe Premiere 2020 was then used for movie and sound integration and movie real-time duration modifications. The duration of the cine-MRI movies was calculated using the real-time timestamps of the first and last DICOM images from each acquisition session. The frame rate was derived from the real-time timestamp of the acquired images. The imaging duration was identified within the audio data and was used to isolate sound samples for subsequent analysis. Using the MRI sound indicative of the MRI acquisition, the audio was selected and aligned to the corresponding initial image. This internal reference sound of image acquisition was used to ensure that imaging correlated exactly to the TMJ sounds.

FIGURE 1
AC-MRI schematic description
A. Simmon T-3 MRI scanner, B. Fiber-optic microphone, OptiRhythm (Optoacoustics, Yehuda Israel) C. Microphone was placed in the area of interest in proximity to TMJ. D. Electro-optical receiver transmitting audio data. E. Audio data and Sound data were recorded on independent computers and later integrated together. Figure created by authors.

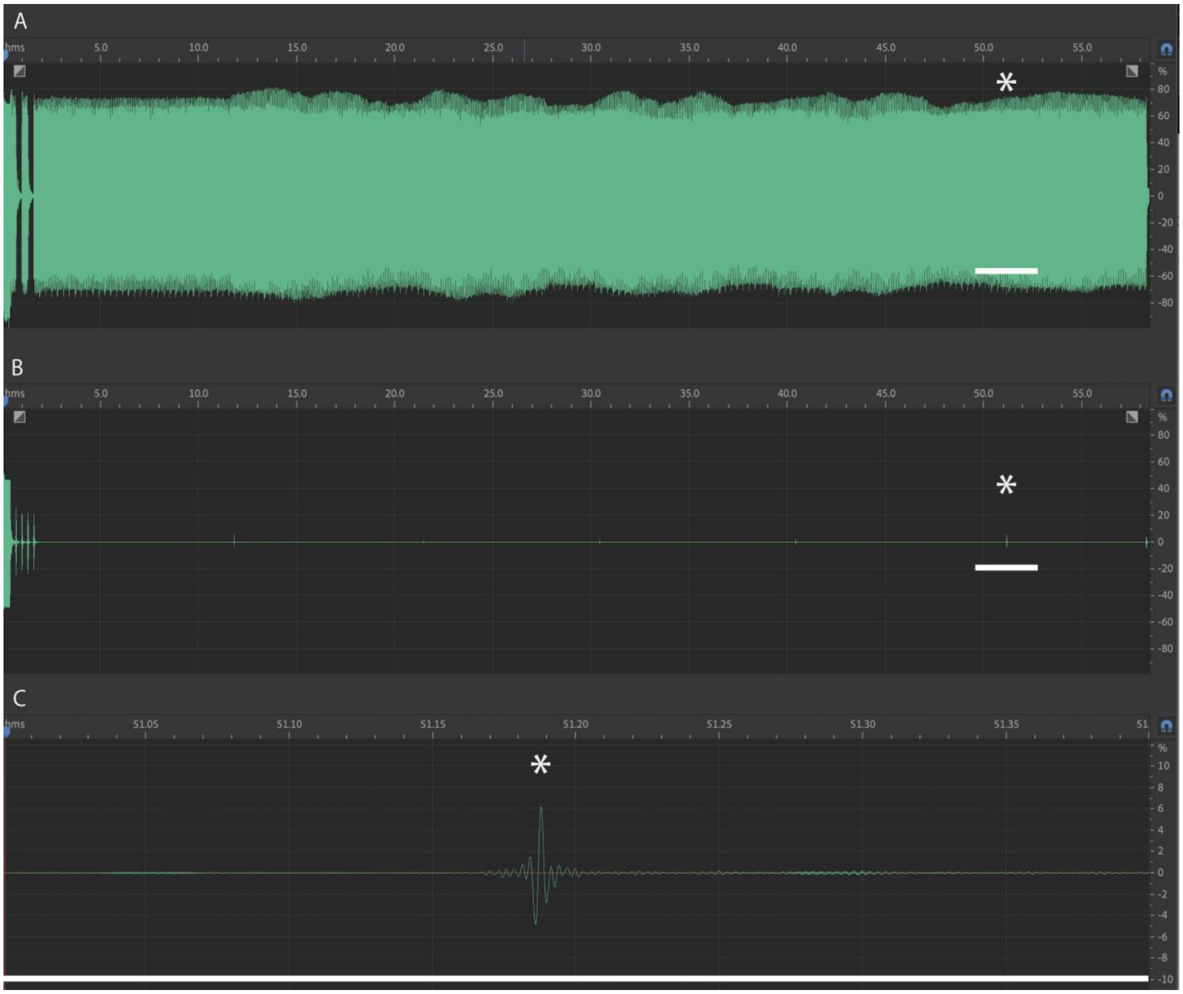

FIGURE 2
Ambient sound reduction and joint sound detection
A. Pre-processed sound. B. Post-processed sound, C. Asterisk (*) indicates a joint sound. Solid white line indicates the region of interest. The X axis is time in seconds and Y axis is the percent (%) of total amplitude

RESULTS

The imaging and sound acquisition technique (AC-MRI) demonstrated successful integration of audio and MRI for the TMJ. This synchronous TMJ audio/MRI recording protocol was shown to be well-tolerated by our subjects. Joint sound was clearly detectable using the OptiRhythm (Optoacoustics, Yehuda Israel) with and without ambient MRI noise during cine-MRI imaging. The FOM was able to detect the sounds from the TMJ that were resolvable despite significant ambient MRI noise.

At the start of the study, in order to assess if joint sounds were resolvable with the FOM the joint sound was first recorded without MRI ambient sound interference. This audio data was comparable to sounds recorded during MRI acquisition after ambient noise was reduced. A representative example of original audio and post-processed audio waveforms appear in Fig. 2. Fig 2. A. demonstrates the pre-processed original sound of a joint recording. Fig. 2. B. Post-processed sound, C. Asterisk (*) indicates a joint sound. Solid white line indicates the region of interest. The X axis is time in seconds and Y axis is the percent (%) of total amplitude.

In all subjects assessed, there were resolvable joint sounds after ambient noise reduction. Multiple recordings of the simultaneous cine-MRI and audio recording were acquired. Representative examples of the recordings can be seen in Figures 3, 4 and 5. In Figure 3-5, the patient underwent both static and dynamic MRI of the TMJ. Figure 5 shows the static images of the joint apparatus showing anterior disc displacement with reduction. The sound wave portion demonstrates imaging of the TMJ apparatus showing anterior disc displacement with reduction as well.

The position and shape of the articular disc-condyle multifaceted was resolvable across sequences of MRI images within the cine-MRI. This was important during analysis because it allowed study members to correlate sound with position of disc during joint movement, and then to compare the dynamic MR images to the more classic still films.

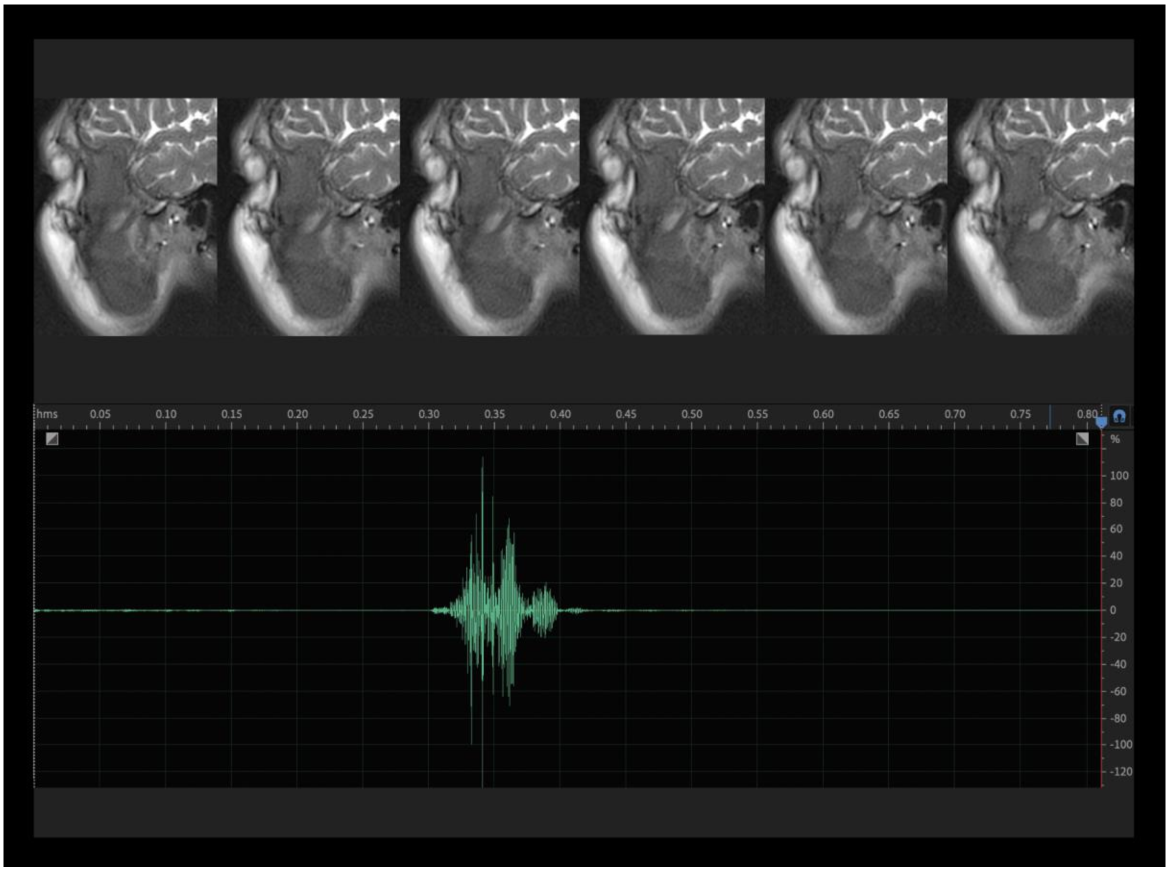

FIGURE 3

Subject 2 AC-MRI. This is a representative joint sound with synchronized imaging from a 22 year old female. Joint sound signal occurs at moment condyle is moving posteriorly during jaw closure.

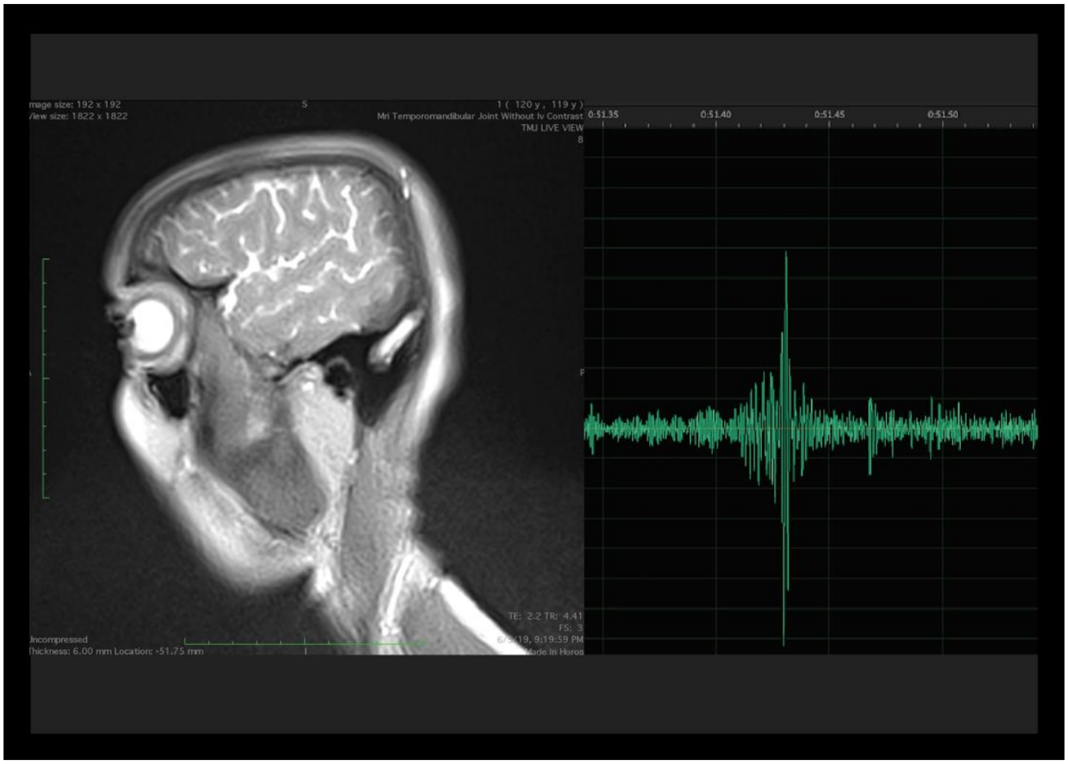

FIGURE 4
Subject 3 AC-MRI. This is a representative joint sound with synchronized imaging from a 24 year old female. A joint sound was detected with joint function.

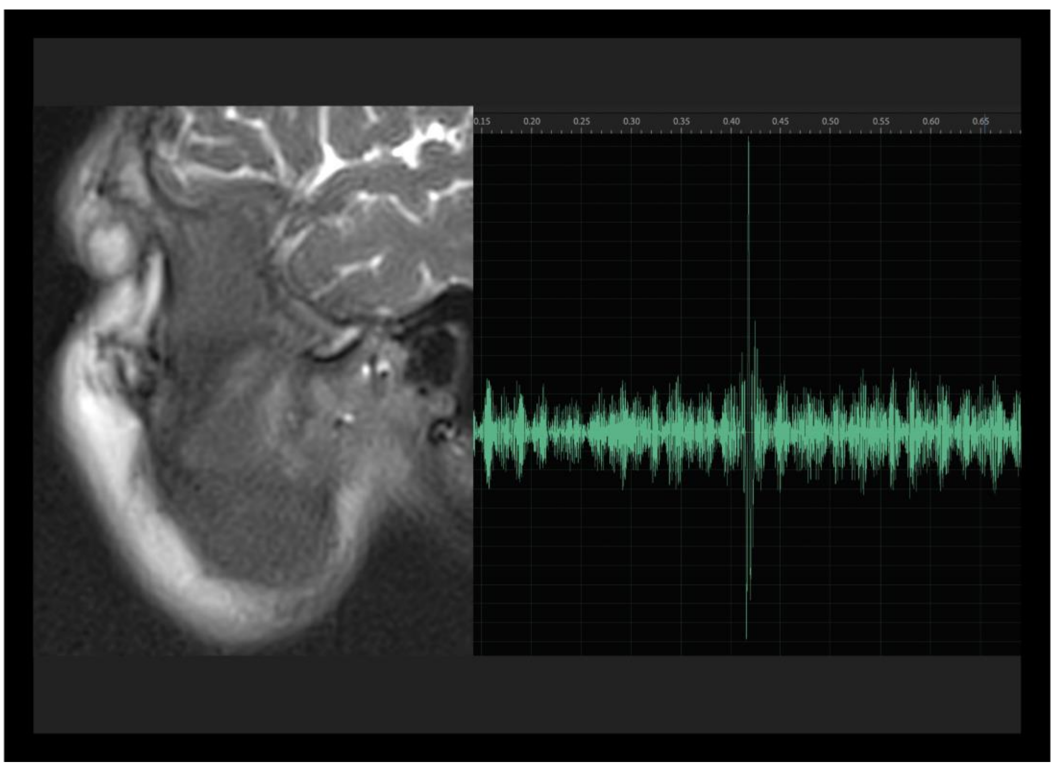

FIGURE 5
Subject 4 AC-MRI. This is a representative joint sound with synchronized imaging from a 24-year-old female. A joint sound was detected while she was performing a closing movement

TABLE 1
Summary of study subject results

Subject	Age/ Gender	MRI Diagnosis	Sound
1	18F	Normal anatomy and function	+
2	22F	Smaller than normal mandibular condyle, flattening of anterior band, and mild degeneration of the posterior band. This joint has recapture but likely anterior subluxation with normal translation.	+
3	24F	Anterior breaking of the condyle and a significantly flattened meniscus. Notable anterior dislocation with partial recapture but normal translation.	+
4	23F	Normal anatomy and function	+

FIGURE 6
Microphone positioning. The subject’s hair was protected with headwrap. The microphone was placed over the TMJ and secured with surgical take. The microphone was further reinforced with surgical tape to minimize movement during the recording session. Figure created by authors.

DISCUSSION

This study shows the first successfully acquired simultaneous MRI and TMJ recorded auscultation in four subjects. Joint sounds were detectable within the audio recordings using the fiber optic microphone. The MR images depict relevant anatomic structures as they are functioning, namely, the disc, condyle, and pterygoid muscles, and are of diagnostic quality. Previous studies have successfully demonstrated recording of high-quality speech during magnetic resonance imaging of the oropharynx and tongue. Thus, protocols have been established for simultaneous cine MRI with audio recordings and analysis of other anatomic systems has been achieved. Similarly, a fiber-optic microphone was used in these studies, however the sound recorded during vocalization is often of a greater intensity than that of the TMJ and the protocol was not compatible with sound recording in this study (21-24). Other groups recorded sound elicited by wind instruments as well as speech affected by velopharyngeal insufficiency, which, again, is of a higher intensity that TMJ sounds (25-27).

The TMJ pop or click sound intensity have been reported at levels that approximate 10-35 dB and the sounds of an MRI scanner can reach sound intensity levels of 125.7 to 130.7 dB (28,29). The acoustic noise of the MRI system originates from ancillary equipment that allows the machine to function at high heat and volume for extended periods of time while an image is acquired.(30) Thus capturing our joint sound signal within the MRI background noise presented considerable challenges. The sound of the MRI signifying initiation of the recording, however, presented an advantage, serving as an internal reference for imaging acquisition, which aided in image and sound synchronization. Therefore, audible recordings of low intensity sound with concurrent MRI recording required use of techniques originally developed for cardiac analysis that were ultimately adapted for the head and neck in this study (21-24).

Previous studies were successful in isolating heart sounds of 13.4-35.0 dB from MRI noise through use of the OPTIRHYTHM microphone (Optoacoustics, Yehuda Israel) (31,32). This system was designed to record heart sounds during a high speed 3-0 cine MRI scan; thus, it was anticipated that this approach might be optimal for study purposes. The microphone provided safe focused digital acquisition of the TMJ sound and ultimately proved to be effective. This noninvasive technique was well-tolerated by subjects and allowed for precise correlation of the functional origin of audible observations. There are limitations to this feasibility study. Additional independent internal reference sounds could further validate the synchronization. Our audio data was interpreted qualitatively (presence or absence of joint sound) and ultimately a quantitative measurement may be achieved in future works (26, 27).

CONCLUSION

This study provides a multi-modal clinical assay that leverages audio and MRI data. Successfully integrating joint sounds to dynamic MR imaging may ultimately lead to a better functional understanding of joint sounds in pathological and non-pathological internal derangements.

RECOMMENDATIONS

Demonstrating that TMJ function can be evaluated using both imaging and audio data has allowed for the above functional correlation. Future analysis may include more detailed measurements such as frequency, intensity or signal to noise ratio, duration and sound categorization. With function of these patients being of the utmost importance, the value of this investigation lies in its ability to diagnose and determine TMJ deviations in real time and may ultimately be used in clinical practice.

References

1. Prinz JF. Physical mechanisms involved in the genesis of temporomandibular joint sounds. J Oral Rehabil. 1998 Sep; 25(9): 706-714. https://doi.org/10.1046/j.1365-2842.1998.00278.x
2. Gay T, Bertolami CN. The acoustical characteristics of the normal temporomandibular joint. J Dent Res. 1988 Jan; 67(1): 56-60. https://doi.org/10.1177/00220345880670011101

3. Gay T, Bertolami CN, Donoff RB, Keith DA, Kelly JP. The acoustical characteristics of the normal and abnormal temporomandibular joint. J Oral Maxillofac Surg. 1987 May; 45(5): 397-407. https://doi.org/10.1016/0278-2391(87)90007-3
4. Ekensten B. Phonograms of anomalies of the temporomandibular joint in motion. Odontol Tidskr. 1952; 60(4): 235-242
5. Schiffman E, Ohrbach R, Truelove E, Look J, Anderson G, Goulet JP, List T, Svensson P, Gonzalez Y, Lobbezoo F, Michelotti A, Brooks SL, Ceusters W, Drangsholt M, Ettlin D, Gaul C, Goldberg LJ, Haythornthwaite JA, Hollender L, Jensen R, John MT, De Laat A, de Leeuw R, Maixner W, van der Meulen M, Murray GM, Nixdorf DR, Palla S, Petersson A, Pionchon P, Smith B, Visscher CM, Zakrzewska J, Dworkin SF; International RDC/TMD Consortium Network, International association for Dental Research; Orofacial Pain Special Interest Group, International Association for the Study of Pain. Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) for Clinical and Research Applications: recommendations of the International RDC/TMD Consortium Network* and Orofacial Pain Special Interest Group†. J Oral Facial Pain Headache. 2014 Winter; 28(1) :6-27. https://doi.org/10.11607/jop.1151
6. Watt DM. Temporomandibular joint sounds. J Dent. 1980; 8: 119-127. https://doi.org/10.1016/0300-5712(80)90027-5
7. Kopp S. Subjective symptoms in temporomandibular joint osteoarthrosis. Acta Odontol Scand. 1977;35(4):207-15. https://doi.org/10.3109/00016357709004656
8. Wilkes CH. Internal derangements of the temporomandibular joint. Pathological variations. Arch Otolaryngol Head Neck Surg. 1989 Apr; 115(4): 469-77. https://doi.org/10.1001/archotol.1989.01860280067019
9. Koh KJ, List T, Petersson A, Rohlin M. Relationship between clinical and magnetic resonance imaging diagnoses and findings in degenerative and inflammatory temporomandibular joint diseases: a systematic literature review. J Orofac Pain. 2009 Spring; 23(2): 123-139
10. Chaput E, Gross A, Stewart R, Nadeau G, Goldsmith CH. The Diagnostic Validity of Clinical Tests in Temporomandibular Internal Derangement: A Systematic Review and Meta-analysis. Physiother Can. 2012 Spring;64(2): 116-134. https://doi.org/10.3138/ptc.2010-54
11. Krohn S, Joseph AA, Voit D, Michaelis T, Merboldt KD, Buergers R, Frahm J. Multi-slice real-time MRI of temporomandibular joint dynamics. Dentomaxillofac Radiol. 2019 Jan;48(1):20180162. https://doi.org/10.1259/dmfr.20180162
12. Bag AK, Gaddikeri S, Singhal A, Hardin S, Tran BD, Medina JA, Curé JK. Imaging of the temporomandibular joint: An update. World J Radiol. 2014 Aug 28; 6(8): 567-582. https://doi.org/10.4329/wjr.v6.i8.567
13. Hopfgartner AJ, Tymofiyeva O, Ehses P, Rottner K, Boldt J, Richter EJ, Jakob PM. Dynamic MRI of the TMJ under physical load. Dentomaxillofac Radiol. 2013; 42(9): 20120436. https://doi.org/10.1259/dmfr.20120436
14. Prinz JF, Ng KW. Characterization of sounds emanating from the human temporomandibular joints. Arch Oral Biol. 1996 Jul; 41(7): 631-639. https://doi.org/10.1016/s0003-9969(96)00070-2
15. Tanzilli RA, Tallents RH, Katzberg RW, Kyrkanides S, Moss ME. Temporomandibular joint sound evaluation with an electronic device and clinical evaluation. Clin Orthod Res. 2001 May; 4(2): 72-78. https://doi.org/10.1034/j.1600-0544.2001.040203.x
16. Christensen LV. Physics and the sounds produced by the temporomandibular joints. Part I. J Oral Rehabil. 1992 Sep;19(5):471-83. https://doi.org/10.1111/j.1365-2842.1992.tb01111.x
17. Sharma S, Crow HC, McCall WD Jr, Gonzalez YM. Systematic review of reliability and diagnostic validity of joint vibration analysis for diagnosis of temporomandibular disorders. J Orofac Pain. 2013 Winter; 27(1): 51-60. https://doi.org/10.11607/jop.972
18. Sun Q, Dong MJ, Tao XF, Yu Q, Li KC, Yang C. Dynamic MR imaging of temporomandibular joint: an initial assessment with fast imaging employing steady-state acquisition sequence. Magn Reson Imaging. 2015 Apr; 33(3): 270-275. https://doi.org/10.1016/j.mri.2014.10.013
19. Abolmaali ND, Schmitt J, Schwarz W, Toll DE, Hinterwimmer S, Vogl TJ. Visualization of the articular disk of the temporomandibular joint in near-real-time MRI: feasibility study. Eur Radiol. 2004 Oct; 14(10): 1889-1894. https://doi.org/10.1007/s00330-004-2418-x
20. Bag AK, Gaddikeri S, Singhal A, Hardin S, Tran BD, Medina JA, Curé JK. Imaging of the temporomandibular joint: An update. World J Radiol. 2014 Aug 28; 6(8): 567-582. https://doi.org/10.4329/wjr.v6.i8.567
21. Shimizu M, Tiede M, Honda K, Shimada Y, Fujimoto I, Nakamura, Ninomiya N. Mri-based speech production study using a synchronized sampling method. J Acous Soc Jpn 1999; 20(5): 375-379. https://doi.org/10.1250/ast.20.375
22. Stone M, Davis EP, Douglas AS, NessAiver M, Gullapalli R, Levine WS, Lundberg A. Modeling the motion of the internal tongue from tagged cine-MRI images. J Acoust Soc Am. 2001 Jun;109(6): 2974-2982. https://doi.org/10.1121/1.1344163
23. NessAiver MS, Stone M, Parthasarathy V, Kahana Y, Paritsky A. Recording high quality speech during tagged cine-MRI studies using a fiber optic microphone. J Magn Reson Imaging. 2006 Jan; 23(1): 92-97. https://doi.org/10.1002/jmri.20463
24. Bresch E, Nielsen J, Nayak K, Narayanan S. Synchronized and noise-robust audio recordings during realtime magnetic resonance imaging scans. J Acoust Soc Am. 2006 Oct; 120(4): 1791-1794. https://doi.org/10.1121/1.2335423

25. ltis PW, Frahm J, Voit D, Joseph AA, Schoonderwaldt E, Altenmüller E. High-speed real-time magnetic resonance imaging of fast tongue movements in elite horn players. Quant Imaging Med Surg. 2015 Jun;5(3): 374-381. https://doi.org/10.3978/j.issn.2223-4292.2015.03.02
26. Sagar P, Nimkin K. Feasibility study to assess clinical applications of 3-T cine MRI coupled with synchronous audio recording during speech in evaluation of velopharyngeal insufficiency in children. Pediatr Radiol. 2015 Feb; 45(2): 217-227. https://doi.org/10.1007/s00247-014-3141-7
27. Nunthayanon K, Honda E, Shimazaki K, Ohmori H, Inoue-Arai MS, Kurabayashi T, Ono T. Differences in Velopharyngeal Structure during Speech among Asians Revealed by 3-Tesla Magnetic Resonance Imaging Movie Mode. Biomed Res Int. 2015; 2015: 126264. https://doi.org/10.1155/2015/126264
28. Sheppard AA, Chen YC, Salvi R. MRI Noise and Hearing Loss. The Hearing Journal. April 2018; 71(4): 30-33. https://doi.org/10.1097/01.HJ.0000532395.75558.2d
29. Gallo LM, Airoldi R, Ernst B, Palla S. Power spectral analysis of temporomandibular joint sounds in asymptomatic subjects. J Dent Res. 1993 May; 72(5): 871-875. https://doi.org/10.1177/00220345930720050701
30. Ravicz ME, Melcher JR, Kiang NY. Acoustic noise during functional magnetic resonance imaging. J Acoust Soc Am. 2000 Oct; 108(4): 1683-1696. https://doi.org/10.1121/1.1310190
31. Nassenstein K, Orzada S, Haering L, Czylwik A, Zenge M, Eberle H, Schlosser T, Bruder O, Müller E, Ladd ME, Maderwald S. Cardiac MRI: evaluation of phonocardiogram-gated cine imaging for the assessment of global and regional left ventricular function in clinical routine. Eur Radiol. 2012 Mar; 22(3): 559-568. https://doi.org/10.1007/s00330-011-2279-z
32. Sakai A, Feigen LP, Luisada AA. Frequency distribution of the heart sounds in normal man. Cardiovasc Res. 1971 Jul; 5(3): 358-363. https://doi.org/10.1093/cvr/5.3.358

* Original research.

How to cite this article: Nudell Y, Gomez J, Vaynblat EF, Hagiwara M, Glickman R. Simultaneous Audio Recording and Magnetic Resonance Imaging of the Temporomandibular Joint. Univ Odontol. 2023; 42. https://doi.org/10.11144/Javeriana.uo42.sarm