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CAVITATION SOUNDS DURING CERVICOTHORACIC SPINAL MANIPULATION

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ABSTRACT

Background: No study has previously investigated the side, duration or number of audible cavitation sounds during high-velocity low-amplitude (HVLA) thrust manipulation to the cervicothoracic spine.

Purpose: The primary purpose was to determine which side of the spine cavitates during cervicothoracic junction (CTJ) HVLA thrust manipulation. Secondary aims were to calculate the average number of cavitations, the duration of cervicothoracic thrust manipulation, and the duration of a single cavitation.

Study Design: Quasi-experimental study

Methods: Thirty-two patients with upper trapezius myalgia received two cervicothoracic HVLA thrust manipulations targeting the right and left T1-2 articulation, respectively. Two high sampling rate accelerometers were secured bilaterally 25 mm lateral to midline of the T1-2 interspace. For each manipulation, two audio signals were extracted using Short-Time Fourier Transformation (STFT) and singularly processed via spectrogram calculation in order to evaluate the frequency content and number of instantaneous energy bursts of both signals over time for each side of the CTJ.

Result: Unilateral cavitation sounds were detected in 53 (91.4%) of 58 cervicothoracic HVLA thrust manipulations and bilateral cavitation sounds were detected in just five (8.6%) of the 58 thrust manipulations; that is, cavitation was significantly ($p < 0.001$) more likely to occur unilaterally than bilaterally. In addition, cavitation was significantly ($p < 0.0001$) more likely to occur on the side contralateral to the clinician's short-lever applicator. The mean number of audible cavitations per manipulation was 4.35 (95% CI 2.88, 5.76). The mean duration of a single manipulation was 60.77 ms (95% CI 28.25, 97.42) and the mean duration of a single audible cavitation was 4.13 ms (95% CI 0.82, 7.46). In addition to single-peak and multi-peak energy bursts, spectrogram analysis also demonstrated high frequency sounds, low frequency sounds, and sounds of multiple frequencies for all 58 manipulations.

Discussion: Cavitation was significantly more likely to occur unilaterally, and on the side contralateral to the short-lever applicator contact, during cervicothoracic HVLA thrust manipulation. Clinicians should expect multiple cavitation sounds when performing HVLA thrust manipulation to the CTJ. Due to the presence of multi-peak energy bursts and sounds of multiple frequencies, the cavitation hypothesis (i.e. intra-articular gas bubble collapse) alone appears unable to explain all of the audible sounds during HVLA thrust manipulation, and the possibility remains that several phenomena may be occurring simultaneously.

Level of Evidence: 2b

Key words: Cavitation, cervicothoracic spine, spinal manipulation, thrust

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Declaration of Interests
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INTRODUCTION

Reductions in pain and disability following high-velocity low-amplitude (HVLA) thrust manipulation to the cervicothoracic region have been widely reported in patients with neck pain[1-11] and shoulder pain.[12-16] However, the frequency, location, and etiology of the cracking, popping or clicking noises that often accompany HVLA thrust manipulative procedures to the spine[17-25] are still poorly understood.[23,26-30]

Four previous studies[31-34] have suggested that the "audible popping" following HVLA thrust manipulation is not related to the clinical outcomes of pain and/or disability. Nevertheless, many clinicians[19,22,35] and researchers[20,21,36-42] still appear to repeat the HVLA thrust manipulation if they do not hear or palpate popping sounds. Moreover, Evans and Lucas[27] proposed the "audible popping", or the "mechanical response" that "occurs within the recipient", should be present to satisfy the criteria for a valid manipulation.[27] However, it remains to be elucidated whether HVLA thrust manipulation to the cervicothoracic spine should normally be accompanied by single, multiple or no cavitation sounds. Furthermore, understanding whether the cavitation phenomenon during cervicothoracic HVLA thrust manipulation is an ipsilateral, contralateral or bilateral event may help inform clinicians in selecting the appropriate manipulation technique that will most effectively target the dysfunctional articulation with the ultimate goal of reducing pain and disability.

The traditional expectation of a single pop or cavitation sound emanating from the target or dysfunctional facet joint during HVLA thrust manipulation[43,44] is not consistent with the existing literature for the upper cervical,[26] lower cervical,[24,45] thoracic[25] or lumbar[17,20,25] regions. Moreover, the evidence suggests that HVLA thrust manipulation directed at the spine creates multiple cavitation sounds.[17,24-26,45] Nevertheless, the question of whether these multiple cavitation sounds emanate from the same joint, adjacent ipsilateral or contralateral joints, or even extra-articular soft-tissues remains to be elucidated.[17,18,20,25,26,46]

To date, only three studies[18,24,26] have investigated the side of joint cavitation during cervical spine manipulation. During "lateral to medial and rotatory" HVLA thrust manipulations targeting the C3-4 facet joint, Reggars and Pollard[24] found 47 (94%) of 50 subjects exhibited "cracking sounds" on the contralateral side to the applicator contact, while two subjects exhibited bilateral sounds and one subject an ipsilateral sound. Additionally, following C3-4 thrust manipulations in 20 asymptomatic subjects, Bolton et al[18] reported cavitation sounds were significantly more likely to occur on the contralateral side to the applicator for "rotation" manipulations, but equally likely to occur on either side during "side-bending" manipulations. Nevertheless, Bolton et al[18] made the assumption that the side with the larger amplitude sound wave was the side of "initial cavitation" and hence did not report if single or multiple cavitations occurred. That is, unless single cavitation events occurred during all cervical manipulations, which is unlikely given the findings of previous studies,[17,20,24,25,45] the possibility remains that the "initial cavitation" occurred on one side, and additional cavitations that were not counted also occurred ipsilaterally and/or contralaterally. Most recently, Dunning et al[26] reported bilateral cavitation sounds in 34 (91.9%) of 37 manipulations, while unilateral cavitation sounds were detected in just 3 (8.1%) manipulations following HVLA thrust manipulation targeting the upper cervical spine (C1-2) articulation. However, it is unknown if the same findings would occur in a different spinal region—i.e. the cervicothoracic junction (CTJ)—and whether using a different HVLA thrust technique with the patient in prone, that is traditionally considered a "lateral break" manipulation[35,47-49] (due to the simultaneous delivery of lateral flexion and lateral translation forces as opposed to primarily employing rotatory forces for the thrusting impulse[35,50]), would alter the side of cavitation and therefore the location of the target articulation that will most likely be effected by the high-velocity thrusting forces.[17,18,20,24,26,28]

Gas bubble collapse,[51] or the cavitation phenomenon, has been traditionally accepted as the mechanism for creating the joint cracking sound.[18,23,27,30,45,51-53] However, a recent study by Kawchuk et al[29] challenged the cavitation hypothesis, and proposed that joint cracking is associated with cavity formation within synovial fluid rather than cavity collapse. Nevertheless, although this first *in-vivo* macroscopic demonstration of tribonucleation was recorded using rapid cine magnetic resonance images on 10 MCP joints, it was from a single subject.[29] Furthermore, the notion that the audible popping sounds were coming from cavity inception, rather than collapse of a pre-existing bubble, is not new and was first proposed by Roston and Haines as early as 1947.[54] However, neither of these two studies[29,54] can be generalized to zygapophyseal joints.

Identifying normative values for the duration of HVLA thrust procedures[23,26,55,56] for different spinal regions may help facilitate a better understanding of the physical parameters surrounding spinal manipulation[28,50,55] (e.g. velocity, acceleration) and the specific psychomotor skills required by practitioners to efficiently perform spinal thrust manipulations.[28,48] Additionally, it still remains to be elucidated whether the popping sounds during HVLA thrust manipulation originate from intra-articular gas bubble collapse, cavity inception within synovial fluid, or extra-articular events.[26,29,30,46,51] Therefore, identifying the duration of individual cavitation sounds,[23,24,26] analyzing the instantaneous energy bursts and frequency content of the sound waves[23,26,45] produced during thrust manipulations may help uncover the etiology[29,46,52,53,57]—i.e. what structures, tissues, or mechanisms are involved—and therefore the relative importance of the audible sounds during thrust manipulations.[27,31,32,34]

For cervical manipulations, the duration of the thrusting procedure has been reported to be 80-200 ms.[23,26,50,55,56] Additionally, using 95% of the instantaneous energy burst—i.e. the amount of energy released in a given sampling interval of the spectrogram—to calculate the duration of single cavitation sounds during upper cervical HVLA thrust manipulation, Dunning et al[26] reported a mean duration of 5.66 ms. However, no study has previously measured the duration of the thrusting procedure or the duration of single cavitation sounds, during HVLA thrust manipulation to the CTJ.

To the best of the authors' knowledge, no study has investigated the side, duration or number of audible cavitation sounds during HVLA thrust manipulation to the cervicothoracic spine. Therefore, the primary purpose of the study was to determine which side of the spine cavitates during cervicothoracic HVLA thrust manipulation. Secondary aims of the study were to calculate the duration of a single cervicothoracic thrust manipulation procedure, and the average number of cavitation sounds following cervicothoracic HVLA thrust manipulation.

METHODS

Participants

Thirty-two individuals with upper trapezius myalgia, i.e. a painful upper trapezius muscle, (20 females and 12 males) were recruited by convenience sampling from a private physical therapy outpatient clinic in Florence, Italy during November of 2013. Their ages ranged between 23 and 65 years with a mean (SD) of 39 (11) years. Height ranged between 152 and 182 cm with a mean (SD) of 170.1 (8.5) cm. Weight was 50.0 kg to 96.0 kg with a mean (SD) of 67.7 (12.6) kg. All subjects reported being physically active, to include walking, running, cycling or regular sports participation.

For subjects to be eligible, they had to present with neck pain for greater than three months, have a primary complaint of a painful spot (i.e., active trigger point) in the upper trapezius muscle, and be between 18 and 65 years of age. The ethics committee at the Universidad Rey Juan Carlos, Madrid, Spain, approved this study. All subjects provided written informed consent before their participation in the study.

Patients were excluded if they exhibited: 1) any red flags (i.e., tumor, fracture, metabolic diseases, rheumatoid arthritis, osteoporosis, resting blood pressure greater than 140/90 mmHg, prolonged history of steroid use, etc.); 2) presented with 2 or more positive neurologic signs consistent with nerve root compression (muscle weakness involving a major muscle group of the upper extremity, diminished upper extremity deep tendon reflex, or diminished or absent sensation to pinprick in any upper extremity dermatome); 3) presented with a diagnosis of cervical spinal stenosis; 4) exhibited bilateral upper extremity symptoms; 5) had evidence of central nervous system disease (hyperreflexia, sensory disturbances in the hand, intrinsic muscle wasting of the hands, unsteadiness during walking, nystagmus, loss of visual acuity, impaired sensation of the face, altered taste, the presence of pathological reflexes); 6) had a history of whiplash injury within the previous three months; or, 7) had prior surgery to the neck or thoracic spine. Of the 33 patients that were invited to enter the study, none refused participation; however, one subject was excluded due to a history of a previous whiplash injury.

Notably, pain or disability scores were not collected in any subjects for two reasons: (1) the primary purpose of this study was to investigate the frequency, location and possible etiologies of the cavitation phenomenon during cervicothoracic HVLA thrust manipulation at a single point in time (i.e. no follow-up period), not to measure changes in pain or disability over time in response to a single manipulation technique given on just one occasion, and (2) all subjects were current patients at a physiotherapy practice in Florence, Italy, and as such, were already receiving conventional physiotherapy treatments for their primary complaint of upper trapezius myalgia. Moreover, significant reductions in pain and disability scores following HVLA thrust manipulation to the cervicothoracic region have already been widely investigated and reported in patients with neck pain[1-11] and shoulder pain.[12-16] However, although cracking, popping or clicking noises often accompany HVLA thrust manipulative procedures,[17-25] the frequency, location and etiology of the cavitation phenomenon itself is still poorly understood.[23,26-30]

Manipulative Physiotherapist

A single, U.S. licensed physical therapist performed all of the cervicothoracic HVLA thrust manipulations in the current study. At the time of data collection, the physical therapist had completed a post-graduate Master of Science in Advanced Manipulative Therapy, had worked in clinical practice for 14 years, and routinely used cervicothoracic HVLA thrust manipulation in daily practice.

Cervicothoracic Junction (CTJ) HVLA Thrust Manipulation Technique

A single "lateral break" HVLA thrust manipulation directed to the CTJ with the patient prone was performed (Figure 1). T1-2 was the target level because this segment is in the center of the three articulations (i.e. C7-T1, T1-T2, T2-3) that are considered to be primarily affected by the manual forces during prone HVLA thrust manipulations to the CTJ.[12,22,28,47,50,58,59] For this technique,[47] the short or lower lever was produced by having the therapist's proximal phalanx, metacarpal, web space and thumb of the right hand contact the superomedial aspect of the patient's right shoulder girdle. The long or upper lever was manufactured by having the therapist place the heel and palm of his left hand over the temporal region of the patient's lateral cranium. To localize the forces to the left T1-2 articulation, secondary levers of extension, lateral flexion, translation and minimal rotation were used. While maintaining the secondary levers, the therapist performed a single HVLA thrust manipulation using the simultaneous delivery of the thrusting primary levers of lateral flexion from the upper lever and lateral translation from the lower lever, i.e., a lateral break. This was repeated using the same procedure but directed to the right T1-2 articulation. Prior to data collection, an independent researcher made random allocation cards using a computer-generated table of randomly assigned numbers;[60] these cards were then used to determine the target side and delivery order of the T1-2 HVLA thrust manipulations for all subjects. Cavitation sounds—i.e. popping or cracking noises—were heard on all HVLA thrust manipulations; hence, there was no need for second attempts.

Figure 1. *High-velocity low-amplitude thrust manipulation directed to the articulation of the left cervicothoracic (T1-2) junction.*

Accelerometer Placement and Sound Collection

Prior to the delivery of cervicothoracic HVLA thrust manipulation, skin mounted accelerometers were secured bilaterally 25 mm lateral to the midline of the T1-T2 interspace (Figure 2). The microphones were connected to a data acquisition system (FOCUSRITE, High Wycombe, Buckinghamshire, U.K., Scarlett 2i2, 96 KHz, 24-bit conversion) and a MacBook Pro laptop with AUDACITY software (Open Source Software, Carnegie Mellon University, Pennsylvania, U.S.A.) for audio acquisition.[26] Sampling frequency was set at 96,000 Hz and the amplitude was normalized by AUDACITY software to values ranging between -1 and +1 (no unit of measurement). With the order of delivery randomized (i.e. right side versus left side), all subjects then received two HVLA thrust manipulations: one targeting the left (T1-2) CTJ, and one targeting the right (T1-2) CTJ. The sound wave signals and resultant cavitation sounds during the cervicothoracic HVLA thrust manipulations were recorded by an individual not involved in data extraction or analysis. Data extraction and processing occurred later and were performed by an individual blinded to target side. Although target side and delivery order were randomly assigned using a computer-generated table of randomly assigned numbers, it was not possible to fully blind the third researcher who performed data analysis because knowledge of target side was required to complete some of the statistical tests—for example, whether cavitation was more likely to occur on the side ipsilateral or contralateral to the clinician's short-lever applicator.

Data Extraction

Short-Time Fourier Transformation (STFT) was used to process the sound signals and obtain spectrograms for each thrust manipulation.[26] A spectrogram is a two-dimensional representation of a signal with time on the x-axis, frequency on the y-axis, and color as a third dimension to express the amplitude, or power of the sound (Figure 3). For each two-channel audio recording, the spectrograms were computed using STFT in order to evaluate the frequency content of both signals over time. The epoch length was set to 0.78 ms (i.e. 75 times the sampling rate) with a 0.1% overlap between adjacent epochs, resulting in a frequency resolution of 94 Hz. The frequency scale was set between 10 Hz and 23 kHz, since this is the audible spectrum for a human being (including a small margin of error).[61]

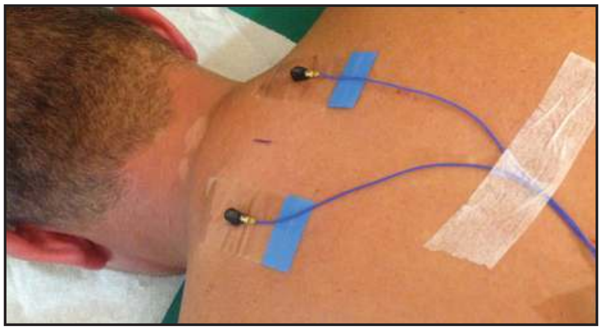

Figure 2. *Bilateral placement and securing of skin-mounted accelerometers 25 mm lateral to the midline of the T1-2 interspace.*

Data Processing

The sound in every audio track was processed as a digital signal with the amplitude varying discretely as a function of time. Each channel was depicted by a separate graph, representing the two recordings of the left and right accelerometers during a single HVLA thrust manipulation to the CTJ. Although the recordings were collected and processed singularly for each person and for each manipulation, we did jointly inspect and analyze the left and right channels for each HVLA thrust manipulation in order to determine whether the cavitation phenomenon was a bilateral, ipsilateral or contralateral event, and in order to accurately sum the total number of cavitations (i.e. pops) during a single manipulation.

In order to isolate the time interval in which the manipulation took place, the audio tracks of the left and right channels (relative to a single manipulation) were first listened to using a stereophonic system. The peculiar sound emitted, together with visual inspection of the right and left graphs of the digital audio signal, allowed for easy recognition of such an interval. The correct time interval featuring the manipulation event was then confirmed and adjusted by decelerating the audio speed by a factor of 0.01 and listening to the track again. This allowed us to identify the beginning and the end of the manipulations (based on sound, not angular movements of the spine), and also to identify how many cavitations (i.e. pops) were present. More specifically, this operation permitted us to increase the resolution of the human ear by 100 fold, allowing us to discriminate and sum the total number of cavitations. Moreover, listening of the audio tracks with a 100-fold deceleration factor and visual inspection of the spectrograms for peaks were both used to determine the number of cavitations present.

The spectrograms show the "location" of the energy of the audio signals over time and over frequency jointly. In figure 3, the spectrograms for the right and left channels for a single HVLA thrust manipulation are depicted, with time on the x-axis, frequency on the y-axis and energy on the z-axis (using a map of colors).

Process for Counting the Number of Cavitations

Per the protocol previously described,[26] the graphs representing the amount of released energy over time in both the left and right accelerometry channels were visually inspected in order to identify instantaneous energy bursts corresponding to cavitations (Figure 4). The total number of cavitations per manipulation was the sum of the number of energy bursts identified.

Process for Determining the Side of Cavitation

For each of the 252 pops generated during 58 cervicothoracic HVLA thrust manipulations, the side of cavitation was determined by inspecting each of the energy bursts for the right and left spectrograms.[26] Since graphs were computed and the amount of energy was quantified at each epoch separately for the two channels, the side of cavitation could be immediately determined by looking at which side the energy burst occurred on. In the event of

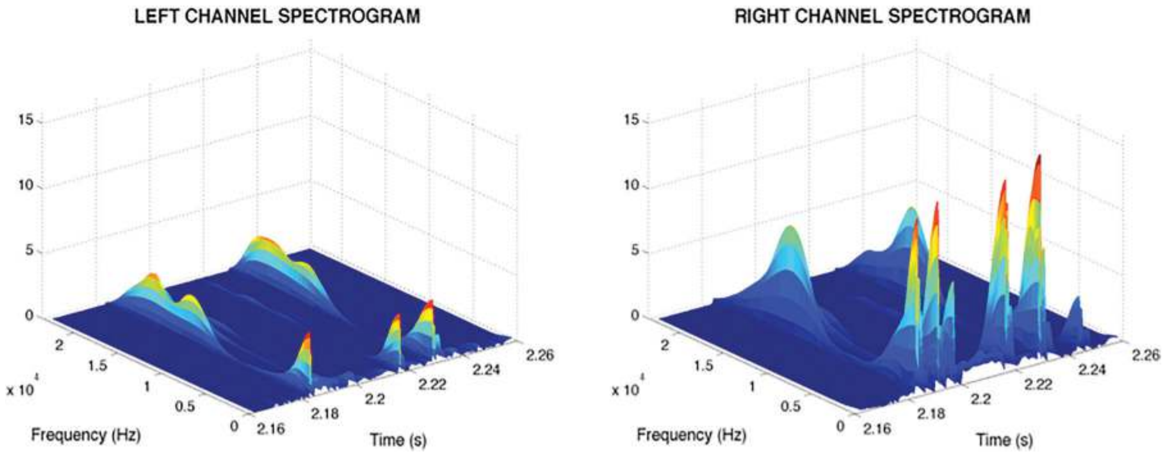

Figure 3. *Spectrograms for the left and right audio channels during cerviothoracic HVLA thrust manipulation. Vertical energy peaks represent individual pops.*

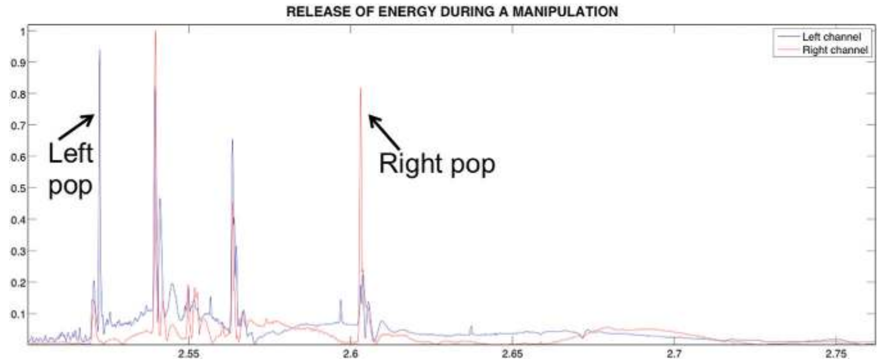

Figure 4. *Amount of energy released over time for the right and left accelerometry channels.*

simultaneous bursts on both channels, the one that began earlier and had the higher energy value was selected; moreover, the smaller and delayed energy burst represented the echo of the original event. A similar methodology for determining the side of cavitation was previously reported for the upper cervical spine.[26]

Process for Calculating the Duration of a Single Cavitation

For each of the 252 cavitations (i.e. popping sounds) detected during 58 cervicothoracic HVLA thrust manipulations, the time interval between the beginning of the ascent of the first energy burst and the end of the descent of the last energy burst of a cavitation event was considered as the duration of a single cavitation (Figure 5).

Process for Calculating the Duration of the Thrust Manipulation

For each thrust manipulation, the time interval between the beginning of first cavitation and the end of the last cavitation was considered as the duration of the thrusting procedure (Figure 6).[26] However, we did not measure the actual forces against time; therefore, the duration of the thrust manipulation likely does not include the time from when the force beyond the preload first began to be applied, or the entire interval from when the peak forces dropped back to zero.[28,48,50]

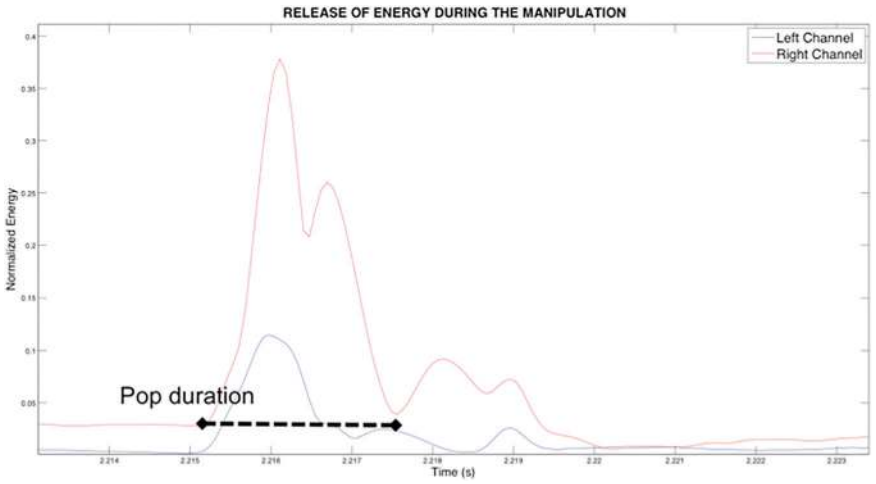

Figure 5. *The time interval used to calculate the duration of a single pop during cervicothoracic HVLA thrust manipulation.*

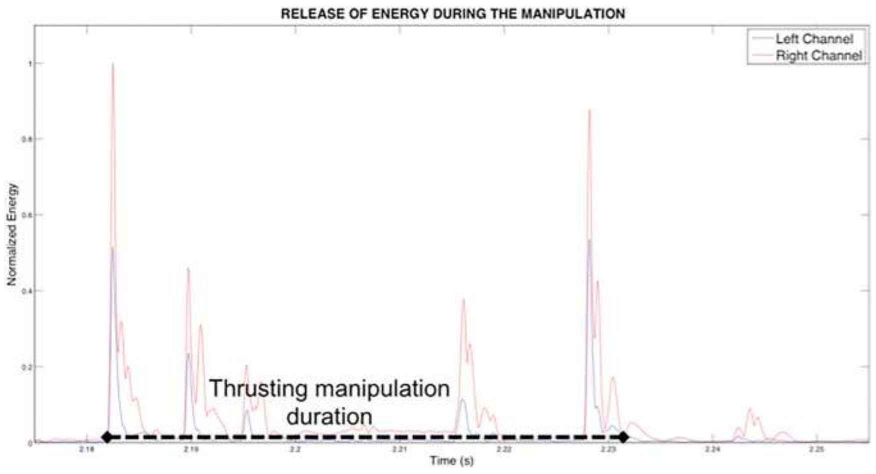

Figure 6. *The time interval used to calculate the duration of cervicothoracic HVLA thrust manipulation.*

Data Analysis

Sound waves resulting from the cervicothoracic HVLA thrust manipulations were displayed in graphical format. Each subject had one right and one left graph corresponding with each thrust procedure (i.e. four graphs in total for each subject). Means and standard deviations were calculated to summarize the average number of pops, the duration of cervicothoracic thrust manipulation, and the duration of a single cavitation. The primary aim, to determine which side of the spine cavitates during CTJ (T1-2) HVLA thrust manipulation, was examined using a Chi-square test. The probability for unilateral or bilateral cavitation events was calculated using the binomial test assuming an expected probability of 50% (i.e. a reference proportion of 0.5). Data analysis was performed using SPSS 23.0.

RESULTS

Subjects ranged between 23 and 65 years of age, with a mean of 39 (SD: 11) years. Of the 252 total cavitations during 58 HVLA thrust manipulations, 22 occurred ipsilateral and 230 occurred contralateral to the targeted T1-2 articulation; that is, cavitation was significantly more likely to occur on the side contralateral to the short-lever applicator of the manipulative physiotherapist ($p < 0.0001$) following right or left thrust manipulation to the CTJ. Moreover, during T1-2 HVLA thrust manipulation targeting the right or left CTJ, the resulting cavitation sounds were 10.5 times more likely to occur on the side contralateral to the short-lever applicator of the manipulative physiotherapist than the ipsilateral side.

All 58 cervicothoracic HVLA thrust manipulations resulted in one or more audible joint cavitation sounds (range, 1-8). Two hundred fifty-two cavitation sounds were detected following 58 cervicothoracic thrust manipulations giving a mean of 4.35 (95%CI 2.88, 5.76) distinct cavitation sounds (i.e. pops or cracks) per cervicothoracic HVLA thrust manipulation procedure. More specifically and on average, for each cervicothoracic HVLA thrust manipulation procedure, 3.97 (SD 1.65) of the 4.35 cavitation sounds (i.e. 91.3%) occurred on the side contralateral to the short-lever applicator of the physiotherapist, whereas, 0.38 (SD 0.75) of the 4.35 cavitation sounds occurred ipsilateral (i.e. 8.7%).

Unilateral cavitation sounds were detected in 53 (91.4%) of the 58 cervicothoracic lateral break HVLA thrust manipulations and bilateral cavitation sounds were detected in just 5 (8.6%) of the 58 thrust manipulations; that is, cavitation was significantly (binomial Test, $p < 0.001$) more likely to occur unilaterally than bilaterally.

One distinct cavitation sound (i.e. a single popping noise) was produced in 4 (6.9%) of the manipulations, whereas 2 (3.5%), 12 (20.7%), 10 (17.2%), 15 (25.9%), 13 (22.4%), 1 (1.7%) and 1 (1.7%) manipulations produced 2, 3, 4, 5, 6, 7 and 8 distinct cavitation sounds, respectively. The mean duration of a single cavitation was 4.13 ms (95%CI: 0.82, 7.46) and the mean duration of a single CTJ HVLA thrust manipulation was 60.77 ms (95%CI 28.25, 97.42).

In addition to single-peak and multi-peak energy bursts, high frequency sounds, low frequency sounds, and sounds of multiple frequencies for each of the 58 cervicothoracic HVLA thrust manipulations were also identified via spectrogram analysis (Figures 3, 5 and 6).

DISCUSSION

Side of the cavitation

The results indicate that cavitation was significantly more likely to occur on the side contralateral to the short-lever applicator of the manipulative physiotherapist following right or left cervicothoracic HVLA thrust manipulation. In addition, unilateral cavitation sounds were detected in 53 (91.4%) HVLA thrust manipulations, while bilateral cavitation sounds were detected in just 5 (8.6%) cases. Resulting cavitation sounds were 10.5 times more likely to occur on the side contralateral to the short-lever applicator of the manipulative physiotherapist than the ipsilateral side. Understanding whether the cavitation phenomenon during cervicothoracic HVLA thrust manipulation is an ipsilateral, contralateral or bilateral event may help inform clinicians in selecting the appropriate thrust manipulation technique that will most effectively target the dysfunctional articulation with the ultimate goal of reducing pain and disability.

Previous authors have investigated the frequency and location of audible cavitations during cervical[18,24,26] and lumbopelvic[17,20] HVLA thrust manipulation; however, this study is the first to report the frequency and side of cavitation during cervicothoracic HVLA thrust manipulation. Additionally, in the current study accelerometers were mounted directly over the target articulation (i.e. 25 mm lateral to the midline of the T1-T2 interspace), whereas both Bolton et al[18] and Reggars and Pollard[24] mounted microphones over the articular pillar and transverse process, respectively, of the C2 vertebra when the target was the C3-4 articulation in each of those studies. Additionally, Bolton et al[18] used a significantly lower sampling frequency of 2000 Hz (compared to 96,000 Hz in our study); thus, they were only able to analyze signal amplitude in the determination for the side of the cavitation. Furthermore, Bolton et al[18] made the assumption that the side with the larger amplitude sound wave was the side of "initial cavitation" and hence did not report if single or multiple cavitations occurred. Unless single cavitation events occurred during all cervical manipulations, which is unlikely given the findings of previous studies,[17,20,24,25,45] the possibility remains that the "initial cavitation" occurred on one side, and additional cavitations that were not counted also occurred ipsilaterally and/or contralaterally at adjacent segments.

Notably, Ross et al[25] found most thoracic and lumbar HVLA thrust manipulations produced two to six audible cavitation sounds with an average error from the target joint of 3.5 cm and 5.29 cm, respectively. Additionally, Beffa and Mathews[17] reported lumbar and sacroiliac HVLA thrust manipulations had low specificity and poor accuracy for the target articulation. Of the 252 total cavitations identified in this study, 22 (8.7%) occurred ipsilateral and 230 (91.3%) occurred contralateral; that is, cavitation was significantly more likely to occur on the side contralateral to the short-lever applicator of the manipulative physiotherapist. Therefore, considering the findings of previous studies[17,20,25] and based on the results of this study, in order to maximize the likelihood that the target articulation is indeed manipulated, it may be appropriate to perform the T1-2 HVLA thrust manipulation with the practitioner standing on the target side of the CTJ, i.e., the short lever applicator on the side opposite the target or symptomatic articulation.

Number of cavitations per thrust

Following 58 cervicothoracic thrust manipulations, 252 cavitation sounds were identified resulting in a mean of 4.35 distinct cavitations (i.e. popping or cracking noises) and a range of one to eight cavitations per T1-2 HVLA thrust manipulation. Similarly, following 37 upper cervical thrust manipulations, Dunning et al[26] reported a mean of 3.57 (range of 1 to 7) cavitations per C1-2 HVLA thrust manipulation. Likewise, Reggars[45] reported 123 individual "joint cracks" resulting in a mean of 2.46 cavitations and a range of 1-5 cavitations per C3-4 HVLA thrust manipulation. Similarly and in agreement with the current study, Reggars and Pollard[24] reported a mean of 2.32 (range of 1 to 5) cavitations per C3-4 manipulation.

Although bubble collapse, or the cavitation model[51] has been widely accepted for the past four decades as the mechanism of "joint cracking",[18,23,27,30,45,51-53] a recent study by Kawchuk et al[29] reported a "dark intra-articular void" during MCP distraction. Notably, this "dark intra-articular void" was associated with concurrent sound production; that is, the "joint cracking" was associated in time with cavity formation (rather than cavity collapse) within the synovial fluid, and with an average of 1.89 mm of joint surface separation. Kawchuk et al[29] referred to this process as tribonucleation; that is, when sufficient distractive force overcomes the viscous attraction or adhesive forces between opposing joint surfaces, rapid separation of the articulation occurs with a resulting drop in synovial pressure, allowing dissolved gas to come out of solution to form a bubble, cavity, clear space or void within the joint.

In this study sounds composed of single energy bursts (i.e. single audible popping sounds) and also sounds composed of multiple energy bursts (i.e. multiple audible popping sounds) were observed. However, whether the multiple cavitation sounds found in this study emanated from the same joint, adjacent ipsilateral or contralateral facet or uncovertebral joints, or even extra-articular soft-tissues remains to be elucidated. In addition to single and multiple energy releases, high frequency sounds, low frequency sounds, and sounds of multiple frequencies were also identified in this study. Therefore, as opposed to the cavitation hypothesis alone being able to explain all of the audible sounds during HVLA thrust manipulation, the possibility remains that several phenomena may be occurring simultaneously. Notably, Shekelle[57] suggested HVLA thrust manipulation may affect the following pathoanatomic lesions: (1) "release of entrapped synovial folds", (2) "disruption of intra- or peri-articular adhesions", (3) "unbuckling of motion segments that have undergone disproportionate displacements", and/or (4) "sudden stretching of hypertonic muscle".[57]

Duration of an individual cavitation

The mean duration of a single cavitation during cervicothoracic HVLA thrust manipulation was 4.13 ms (95% CI: 0.82, 7.46) in this study. This value approximates the 4 ms duration reported by Reggars and Pollard[24] for the "average length of joint crack sounds" and the 5.66 ms duration reported by Dunning et al[26] for the mean duration of a "single pop" during upper cervical thrust manipulation. Nevertheless, Herzog et al[23] reported triphasic "cavitation signals" with a mean duration of 20 ms, however, it is unclear whether this value represents single or multiple cavitation sounds. Unlike previous studies,[23,24,26] the time interval between the beginning of the ascent of the first energy burst and the end of the descent of the last energy burst of a cavitation event was calculated and used for the duration of a single pop in this study. Therefore, the interval was representative of the duration of 252 individual cavitation sounds (i.e. popping or cracking noises) detected during 58 cervicothoracic HVLA thrust manipulation procedures.

Duration of the thrust procedure

Similar to Dunning et al,[26] but unlike three previous studies,[23,55,56] the time interval between the beginning of first cavitation and the end of the last cavitation was used to represent the duration of the actual thrusting procedure from onset to arrest in the current study; nevertheless, the mean duration of a single cervicothoracic HVLA thrust manipulation was found to be 60.77 ms (95%CI 28.25, 97.42), a value that is slightly shorter but still consistent with Triano[56] (135 ms), Herzog et al[23] (80-100 ms), Ngan et al[55] (158 ms) and Dunning et al[26] (97 ms). Notably, Triano[56] measured the duration of the thrusting procedure by analyzing force-time history graphs for a C2-3 lateral break manipulation; whereas, Ngan et al[55] used a four camera motion analysis system to measure head on trunk angular movements (and indirectly thrust duration) during lower cervical rotational manipulations in eight asymptomatic subjects. Additionally, Herzog et al[23] measured thrust duration using "instantaneous acceleration signals" from a mechanical accelerometer during T4 posterior to anterior thrust manipulations in 28 subjects with thoracic pain. Therefore, considering the different instrumentation and analytical methods used in each of the previous studies,[23,26,55,56] there does not appear to be a consistent reference standard for measuring thrust duration. Nevertheless, to date, this study is the first to report the thrust duration for a manipulation technique that targets the T1-2 articulations.

Clinical relevance of the cavitation sounds

The cavitation sound is traditionally considered by many physical therapists, chiropractors, and osteopaths to be an important indicator for the successful technical delivery of an HVLA thrust manipulation.[19,20,22,23,25,35,39,40,56] However, four previous studies[31-34] have suggested that the "audible pop" following HVLA thrust manipulation is not related to the clinical outcomes of pain and/or disability. Nevertheless, these authors[31-34] investigated the thoracic and lumbopelvic regions, not the cervical spine or CTJ. Notably, many clinicians[19,22,35] and researchers[20,21,36-42] still appear to repeat the HVLA thrust manipulation if they do not hear or palpate popping sounds. Moreover, Evans and Lucas[27] proposed the "audible popping", or the "mechanical response" that "occurs within the recipient", should be present to satisfy the criteria for a valid manipulation.[27] Understanding whether the cavitation phenomenon during cervicothoracic HVLA thrust manipulation is an ipsilateral, contralateral or bilateral event will help inform practitioners of spinal manipulative therapy in selecting the appropriate technique that will most effectively target the dysfunctional articulation with the ultimate goal of reducing pain and disability. More specifically, considering the findings of previous studies[17,20,25] and based on the results of our study, in order to maximize the likelihood that the target articulation is indeed manipulated, the practitioner should stand on the target side of the

CTJ when performing a "lateral break" cervicothoracic HVLA thrust manipulation with the patient in prone, i.e., the short lever applicator of the practitioner should be placed on the side opposite the target or symptomatic articulation.

Limitations

It should be recognized that the morphology and arthrokinematics of the zygapophyseal joints are distinct to this region; thus, the results should be extrapolated to other spinal regions with caution. Furthermore, the results of this study cannot be generalized to cervicothoracic manipulation techniques that use different combinations of primary, secondary, physiologic and accessory component levers. One further limitation of this study is that only one practitioner administered all of the cervicothoracic thrust manipulations; while this enhances internal validity it also compromises generalizability. Future research should determine the vertebral levels at which the cavitation sounds are emanating from and investigate the clinical significance of the cavitation phenomenon following cervicothoracic HVLA thrust manipulation to determine whether a relationship exists between the number of cavitations and change in the clinical outcomes of pain and disability in various subgroups of patients.

CONCLUSIONS

Cavitation was significantly more likely to occur unilaterally, and on the side contralateral to the short-lever applicator contact, during cervicothoracic HVLA thrust manipulation. Most subjects produced three to five cavitations (i.e. popping or cracking noises) during a single lateral break HVLA thrust manipulation targeting the right or left T1-2 articulation; therefore, practitioners of spinal manipulative therapy should expect multiple cavitation sounds when performing HVLA thrust manipulation to the CTJ. Furthermore, the traditional manual therapy approach of targeting a single ipsilateral or contralateral facet joint during the delivery HVLA thrust manipulation may not be realistic. Whether the multiple cavitation sounds found in this study emanated from the same joint, adjacent ipsilateral or contralateral facet or uncovertebral joints, or even extra-articular soft-tissues remains to be elucidated. Due to the presence of multi-peak energy bursts and sounds of multiple frequencies, neither the cavitation hypothesis (i.e. intra-articular gas bubble collapse) nor the tribonucleation hypothesis (i.e. cavity inception within synovial fluid) alone appear able to explain all of the audible sounds during HVLA thrust manipulation, and the possibility remains that several phenomena may be occurring simultaneously.

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