Objective: To determine the role played by the tensor veli palatini and levator veli palatini muscles (mTVP and mLVP, respectively) in eustachian tube (ET) opening.

Design: Prospective study.

Setting: Research laboratories at a tertiary care hospital.

Patients: Fifteen healthy adults with normal middle ears and documented ET openings.

Interventions: Submental and ground surface electrodes were placed. After anesthetizing and decongesting the nasal passages, paired electromyographic needle electrodes were inserted into both the mTVP and mLVP on the test side. A microphone was placed into the ipsilateral ear canal and the probe from a sound generator was introduced into the opposite nostril. A 45° telescope was used on the test side to video-record the soft palate and ET movements while the individual swallowed.

Main Outcome Measures: Concurrent recordings of the ET openings by sonotubometry, the electromyographic activity for the LVP, TVP, and submental muscles, and video of the nasopharyngeal orifice of the ET during swallowing.

Results: During swallowing, the median peak amplitude and duration of ET openings by sonotubometry were 30.6 mV and 196 milliseconds, respectively. For the mLVP and mTVP, the median peak amplitudes were 0.33 and 0.82 mV, and peak durations were 131 and 85 milliseconds, respectively. The mean onsets of muscle activity referenced to the sonotubometry peak amplitude were −0.28, −0.24, and −0.14 milliseconds for the mLVP, mTVP, and submental muscles, respectively. Video recording of ET movements were consistent with the timing of these events.

Conclusions: The mTVP activity had a shorter duration but greater amplitude than the mLVP activity and was associated with peak ET opening by sonotubometry. The mLVP activity occurred before that of the mTVP, the submental muscle group, and peak ET opening. The mLVP contractions were associated with movements of the soft palate, anterior ET orifice, and rotation of the ET cartilage.
METHODS

PARTICIPANTS

Healthy adult (≥18 years) volunteers were recruited from the surrounding community by advertisement. After obtaining informed consent approved by the University of Pittsburgh institutional review board, participants were screened for general health, OM history, prior nasal and/or facial surgery, and a standard ear, nose, and throat examination was performed. Inclusion criteria included (1) no reported history of ME disease or nasal or facial reconstructive surgery, (2) no known allergic or previous reactions to lidocaine hydrochloride and oxymetazoline hydrochloride, (3) an unobstructed nasal airway that allowed endoscope passage to the posterior nasopharynx, (4) a normal nasal and facial anatomy, and (5) at least 1 successful ET opening in a sequence of 3 repeated sonotubometric tests.

INSTRUMENTATION

The data were collected using an Octal Bio Amp (model ML138) interfaced to a Power Laboratory 8/30 A-D module (model ML870) (both, AD Instruments Pvt Ltd). The video stream from the DigiCam 2.0 (JedMed Instrument Co) was fed through a USB port where it was collated with the signals from the PowerLab in the LabChart software (version 7.2; AD Instruments Pvt Ltd) running on an HP-Compaq dc5800 personal computer (Hewlett-Packard).

PROTOCOL

The experimental setup was accomplished in a staged manner with the data stream from each added test modality evaluated prior to proceeding. Initially, both nasal cavities were topically anesthetized and decongested (lidocaine hydrochloride, 4%; Roxane Laboratories Inc) and oxymetazoline hydrochloride, 0.05% (Major Soothing 12 Hour Nasal Decongestant Spray; Major Pharmaceuticals) mixed 1:1 with spray followed by soaked cotton gauze (Medtronic Neuray Neurosurgical Patties, 0.5 × 2.0 in; Medtronic Xomed Inc). This procedure was repeated until satisfactory local anesthesia and decongestion were obtained. Both nasal cavities were evaluated with a 0° endoscope (Hopkins, 2.7 mm in diameter and 18 cm in length; Karl Storz Endoscopy), attached to a digital videocamera (DigiCam 2.0, JedMed Instrument Co), to determine the optimum side for the experimental procedure. Submental surface electrodes (Narxion Dual Electrodes, Noraxon USA Inc) were placed on the experimental side along the anterior belly of the digastric muscle with a surface reference electrode (Medtricure 100, ECG Conductive Adhesive Electrodes, Tyco Healthcare Group LP) attached to the mastoid tip, and the EMG signal was checked. Next, the participants were instrumented for sonotubometry by inserting a microphone into the external ear canal on the test side and covering both ears with a standard ear protector. A white-noise probe tone (110 dB at speaker source) was introduced into the ipsilateral nostril, and the sonotubometric and submental EMG data streams were verified. This completed the first phase of the setup in which biological signals of swallowing were established.

In the second phase of the setup, we established the conditions for visualizing the ET nasopharyngeal orifice and for placing the intramuscular EMG electrodes. The anesthetized and decongested region of the nasal cavity was extended posteriorly on the experimental side using a second set of soaked cotton patties. The ipsilateral nasopharynx and ET were examined in more detail using a 45° telescope (Hopkins, 2.7 mm in diameter and 18 cm in length; Karl Storz Endoscopy) with the attached videocamera. Last and in succession, 2 sets of disposable paired stainless steel insulated fine-wire EMG electrodes (0.002 × 8 in, Chalgreen Enterprises Inc) fitted within 4.75-in, 23-g spinal needles for guidance and insertion (Spinocan, B. Braun Medical Inc) were advanced through the ipsilateral nasal cavity under endoscopic visualization. One pair of electrodes was inserted into the belly of the mTVP just anterior to the nasopharyngeal orifice of the ET, and the needle was removed. The second pair of electrodes was inserted into the belly of the mLVP just medial and inferior to the floor of the ET, and the needle was removed (Figure 1). The electrode wires were attached via spring contacts to an anchored fine-wire board (AFWA-0, Noraxon), which was in turn connected to the Octal Bio Amp.

Data were collected simultaneously from 5 data streams: the submental electrode, sonotubometry, videendoscopy, and the
fine-wire electrodes in the mLVP and mTVP. These streams were amplified, rectified, and smoothed to produce signals for analysis (Figure 2). Initially, the participant was asked to perform 3 repetitions of 3 maneuvers: voicing (1) k-k-k and (2) uh, uh, uh and (3) yawning to verify the activity of each part of the data stream. The primary experiment consisted of 3 saliva swallows at 10-second intervals while the movements of the nasopharyngeal orifice of the ET was observed and recorded through the 45° endoscope. Electronic labels were affixed to the data streams by the technician as each maneuver was performed. After the completion of these recordings, the 45° endoscope was withdrawn and the electrodes were removed. A repeated endoscopy was performed with a 0° telescope to verify lack of bleeding before discharging the participant.

DATA ANALYSIS

The data used for analysis were derived from the 3 saliva swallows. The LabChart Peak Analysis extension was used to identify and quantify the data peaks obtained during those swallows. On average, peaks exceeded baseline values by at least 20 baseline standard deviations (data not shown). The parameters recorded for each peak included the amplitude, area, and width at 50% peak height. We also calculated the interval between the sonotubometric peak and the onset of the submental musculature, mTVP, and mLVP EMG activities. Each participant was represented by the mean value of the 3 peaks for each parameter for each study variable.

Then, video images were examined and coded by one of the investigators (C.M.A.) blinded to the participant’s EMG data. Using the LabChart software, the video images were reviewed frame by frame. First, he identified the still frame in which the greatest opening of the nasopharyngeal orifice of the ET occurred. This frame was designated as frame 0, and all other frames were labeled with respect to it, negative or positive values occurring before and after the reference frame, respectively. For the frame, the elevation of the soft palate with displacement and axial rotation of the medial lamina of the ET cartilage were attributed to mLVP activity, and the posterior displacement of the lateral wall of the ET lumen opening was attributed to mTVP activity. These soft-tissue movements were categorized on a scale of 0 to 4 relative from a value of 0 at the relaxed state to a value of 4 at the maximum displacement of the tissue. The duration of the swallowing event was defined as the time for a full cycle of activity (ie, relaxed state to motion state to relaxed state for all structures).

RESULTS

A total of 20 participants were enrolled (11 were male; 1 was Asian; 10, white; 9, black). The mean (SD) age of the patients was 36 (10) years (range, 19-54 years). Data from 3 early participants were excluded because of significant technical issues associated with technique development or equipment malfunction. In 2 participants, there were no distinct EMG recordings from either the mTVP or mLVP and, in 1 and 3 participants; EMG data were not obtained from the mLVP or mTVP, respectively. We attribute these failures to difficulties in electrode placement and not to an absence of muscle activity. Thus, in 15 participants (mean [SD] age, 36 [11] years; 8 were black; 6, white; 1, Asian; 8, female; and 7, male) EMG recordings were achieved for either the mLVP or mTVP, and complete EMG data from the mLVP, mTVP, and submental muscles were available for 11 participants.

The Table reports the mean (SD), median, and range of the sonotubometric and EMG parameters for the 15 participants. Overall, mTVP activity had a shorter duration but greater amplitude than mLVP activity. The mLVP activity occurred before that of the mTVP and the submental muscle group (Figure 3).

Endoscopic findings during swallowing averaged for all participants are summarized in Figure 4. By definition, maximum opening of the ET lumen (in black circles) occurred at frame 0. The maximum range of a swallow was captured in 21 frames, 10 frames prior to and 10 frames after frame 0. The first anatomical change observed during a swallow was the elevation of the soft palate as indicated in Figure 4 by the onset of mLVP con traction. The posterior displacement and axial rotation of the medial lamina of the ET cartilage mirrored mLVP activity with a slight delay relative to the onset of a swallow. The average posterior displacement of the lateral wall...
of the ET lumen corresponded to the mTVP contraction and approximated the timing of maximum ET opening. Video recording of the ET openings were consistent temporally with the EMG activity of the paratubal muscles and with the ET openings as measured by the peak amplitude of the sonotubometry microphone.

A variety of methods to assess the opening function of the ET have been described, but most require direct access to the ME airspace (either through a perforated tympanic membrane or a patent tympanostomy tube) and therefore are usually limited to evaluations of pathologic MEs.1 Alternatively, sonotubometry and videoendoscopy of the nasopharyngeal orifice of the ET were developed for assessing ET opening in ears with an intact tympanic membrane,4,5,16-18 and EMG of the paratubal muscles was used to determine if poor ET opening could be attributed to abnormal activities and/or timing of the mTVP and/or mLVP activity.6-14

Sonotubometry is a well described acoustic method for assessing tubal opening (magnitude and duration) during various nasopharyngeal maneuvers, such as swallowing, yawning, and mandibular repositioning.16,17 Briefly, a probe sound is introduced into the nose, which is monitored by microphones in the external ear canals. The ET opening is documented as an increase in sound amplitude (proportional to microphone voltage) in the external ear canal during activities that dilate the tube (eg, swallowing, yawning, jaw movement, etc).

Videoendoscopy of the nasopharyngeal orifice of the ET is a relatively old procedure used to visualize the relative movements of the palate, paratubal muscles, and ET orifice during those activities that typically open the ME airspace.

### Table. Summary Results for Each Recorded Variable of the Functions Reflecting ET Opening (Sonotubometry) and the EMG Activities of the mLVP, mTVP, and the Submental Muscles

<table>
<thead>
<tr>
<th>Function</th>
<th>Parameter</th>
<th>No.</th>
<th>Mean (SD)</th>
<th>Median (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sono</td>
<td>Peak amplitude, mV</td>
<td>15</td>
<td>30.6 (30.5), mV</td>
<td>19.0 (2.7 to 117.5), mV</td>
</tr>
<tr>
<td></td>
<td>Peak area, mVs</td>
<td>15</td>
<td>8.74 (11.53), mVs</td>
<td>3.75 (0.26 to 41.40), mVs</td>
</tr>
<tr>
<td></td>
<td>Peak width 50, ms</td>
<td>15</td>
<td>196 (76), ms</td>
<td>203 (68 to 321), ms</td>
</tr>
<tr>
<td>mLVP EMG</td>
<td>Peak amplitude, mV</td>
<td>14</td>
<td>0.33 (0.19), mV</td>
<td>0.31 (0.12 to 0.87), mV</td>
</tr>
<tr>
<td></td>
<td>Peak area, mVs</td>
<td>14</td>
<td>0.06 (0.04), mVs</td>
<td>0.04 (0.00 to 0.15), mVs</td>
</tr>
<tr>
<td></td>
<td>Peak width, 50 ms</td>
<td>14</td>
<td>131 (122), ms</td>
<td>70 (42 to 449), ms</td>
</tr>
<tr>
<td></td>
<td>Start peak relative sono peaks, sec</td>
<td>14</td>
<td>-0.28 (0.30), sec</td>
<td>-0.27 (-0.73 to 0.34), sec</td>
</tr>
<tr>
<td>mTVP EMG</td>
<td>Peak amplitude, mV</td>
<td>12</td>
<td>0.82 (1.27), mV</td>
<td>0.42 (0.23 to 4.81), mV</td>
</tr>
<tr>
<td></td>
<td>Peak area, mVs</td>
<td>12</td>
<td>0.13 (0.34), mVs</td>
<td>0.03 (0.00 to 1.22), mVs</td>
</tr>
<tr>
<td></td>
<td>Peak width, 50 ms</td>
<td>12</td>
<td>85 (65), ms</td>
<td>59 (27 to 199), ms</td>
</tr>
<tr>
<td></td>
<td>Start peak relative sono peaks, sec</td>
<td>12</td>
<td>-0.24 (0.33), sec</td>
<td>-0.29 (-0.76 to 0.48), sec</td>
</tr>
<tr>
<td>Submental</td>
<td>Peak amplitude, mV</td>
<td>11</td>
<td>9.86 (21.81), mV</td>
<td>0.10 (0.00 to 61.84), mV</td>
</tr>
<tr>
<td></td>
<td>Peak area, mVs</td>
<td>11</td>
<td>1.57 (3.49), mVs</td>
<td>0.00 (0.00 to 8.84), mVs</td>
</tr>
<tr>
<td></td>
<td>Peak width, 50 ms</td>
<td>11</td>
<td>160 (110), ms</td>
<td>150 (37 to 431), ms</td>
</tr>
<tr>
<td></td>
<td>Start peak relative sono peaks, sec</td>
<td>11</td>
<td>-0.14 (0.46), sec</td>
<td>-0.20 (-0.75 to 0.68), sec</td>
</tr>
</tbody>
</table>

Abbreviations: EMG, electromyography; ET, eustachian tube; mLVP, levator veli palatini muscle; ms, milliseconds; mTVP, tensor veli palatini muscle; mVs, millivolt-seconds; sec, seconds; sono, sonotubometry.
tube. Briefly, a fiber-optic endoscope attached to a video camera is advanced through the anesthetized side of the nose to the region of the nasopharynx and focused on the ipsilateral ET. This positioning allows the nasopharyngeal orifice of the ET to be examined (and recorded) to document any localized disease either intrinsic (inflammation) or extrinsic (e.g., adenoids) to the ET orifice. Also, the movements effected by the mTVP and mLVP during different maneuvers can be recorded and related to those of the soft palate, nasopharyngeal wall, and ET orifice. Takahashi et al hypothesized that abnormal results on this test reflect abnormal activities of the paratubal muscles and ET dysfunction.

Electromyography was used to study the activities of the mTVP and mLVP during nasopharyngeal maneuvers. The first such studies used transoral placement of a unipolar electrode into the mTVP and transexternal ear canal placement of an electrode into the tensor tympani muscle of anesthetized patients undergoing ME surgery. Those results showed that EMG activities could be reliably recorded from the 2 muscles, confirmed the anatomical observation of continuity of the 2 muscles, and demonstrated that this combined muscle system showed reliable, coordinated EMG activity in response to broadband noise and swallowing but not to other stimuli.7 Later studies used a transnasal approach, guided by nasopharyngeal endoscopy, to insert unipolar EMG electrodes into the anterior regions of the mTVP or mLVP in patients with and without ME disease. The EMG recordings of the mLVP and mTVP activities in patients with resolving OM secondary to resected nasopharyngeal carcinoma showed differences in mTVP activity between the affected and nonaffected sides, but no differences were reported for otherwise healthy participants with or without OM. However, because these studies did not concurrently assess the function of both muscles, it is not known if the timing of mTVP and mLVP activity underlies the reported abnormal movements of the ET system, as seen with videendoscopy. Indeed, computer modeling suggests that the firing sequence for the 2 muscles during swallowing may be the determining factor in tubal opening. The latter requires simultaneous recording from both the mTVP and mLVP, previously only accomplished in monkeys. Extrapolation of those results to humans may be unwarranted owing to differences in the anatomy and physiologic characteristics of the ET system between the 2 species.

In the current study of healthy adults with no history of OM, we combined these 3 modalities in an attempt to describe the temporal relationships for ET opening assessed by sonotubometry, the activities of the mTVP and mLVP assessed by EMG and the movements of the soft palate and ET orifice assessed by videendoscopy of the soft palate and nasopharynx. The videendoscopic results showed that elevation of the palate preceded sonotubometric ET opening while posterolateral displacement of the lateral wall of the ET corresponded to actual ET dilation. Furthermore, these ET movements, correlated with contraction of the mLVP and to a later contraction of the mTVP, respectively. Based on these results, we achieved the primary goal of this study, which was to demonstrate the feasibility of this method laying the foundation for future studies using these techniques in adults and older children with OM, ET dysfunction, or a history of those conditions.

In conclusion, to our knowledge this is the first report to describe concurrent monitoring of sound transmission through the ET, EMG activity of the mTVP and mLVP, and direct visualization of ET and soft palate movements attributable to contractions of the paratubal muscles during a swallow. Certain temporal relationships between these measures were described for this adult, normal population. Multimodal assessment of ET function using these methods is a novel and promising method for expanding our knowledge of ME physiologic and pathophysiologic mechanisms.

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REFERENCES