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Intrinsic Measures and Shape Analysis of the Intratemporal Facial Nerve

Short Read: Shape Analysis of the Facial Nerve

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ABSTRACT

Hypothesis: To characterize anatomical measurements and shape variation of the facial nerve within the temporal bone, and to create statistical shape models (SSMs) to aid in automated segmentation.

Background: The facial nerve is a fundamental structure in otologic surgery, and detailed anatomic knowledge with surgical experience are needed to avoid its iatrogenic injury. Trainees can utilize simulators to practice surgical techniques, however manual segmentation required to develop simulations can be time consuming. Consequently, automated segmentation algorithms have been developed that use atlas registration, SSMs, and deep learning.

Methods: Forty cadaveric temporal bones were evaluated using three dimensional microCT (μCT) scans. The image sets were aligned using rigid fiducial registration, and the facial nerve canals were segmented and analyzed. Detailed measurements were performed along the various sections of the nerve. Shape variability was then studied using two SSMs: one involving principal component analysis (PCA) and a second using the Statismo framework.

Results: Measurements of the nerve canal revealed mean diameters and lengths of the labyrinthine, tympanic and mastoid segments. The landmark PCA analysis demonstrated significant shape variation along one mode at the distal tympanic segment, and along three modes at the distal mastoid segment. The Statismo shape model was consistent with this analysis, emphasizing the variability at the mastoid segment. The models were made publicly available to aid in future research and foster collaborative work.

Conclusion: The facial nerve exhibited statistical variation within the temporal bone. The models used form a framework for automated facial nerve segmentation and simulation for trainees.

Keywords: Facial nerve, temporal bone, statistical shape model, computed tomography, chorda tympani, anatomic variations, segmentation, surgical simulation

BACKGROUND

The facial nerve is a fundamental structure in the study of head and neck anatomy. Being the seventh cranial nerve, it serves primarily by innervating the muscles of facial expression, and therefore is necessary for emotional expression, speech and mastication. Additionally, it contributes to taste, lacrimation, salivation, and some cutaneous sensation. The nerve initially emerges from the brainstem at the cerebellopontine angle and travels with the vestibulocochlear nerve in a short segment laterally to the internal auditory canal (IAC). From here, it begins its course through the fallopian canal of the temporal bone. This canal is notable as it is the longest bone-laden nerve canal in the body [1], is subject to great variation in its anatomical course [2], and shares intimate borders with many of the essential structures of the ear. Therefore, there is considerable importance in the knowledge and study of this path for both the anatomist and the otologic surgeon.

The intratemporal path of the facial nerve has been described in a number of previous texts[1,3,4], and a graphic representation can be seen in **Error! Reference source not found.**. Early quantitative analysis used computed tomography (CT) to measure the length of each segment, ranging from 2.5 to 6mm, 8 to 11mm, and 8.9 to 16mm for the labyrinthine, tympanic, and mastoid, respectively [5]. Diameter has been evaluated in several studies, with smaller canals being correlated to increasing incidences of Bell's palsy [6]. Fisch *et al.* initially focused on the entrance of the facial nerve from the IAC at the meatal foramen, as it is one of the smallest areas, averaging only 0.68mm in diameter [7]. Nakashima et al. later described a second bottleneck in the midtympanic segment [8]. More recently, Vianna *et al.* measured the diameter at this tympanic midpoint, along with the labyrinthine and mastoid, as 1.9, 1.7 and 2.6mm respectively. Significant differences between control and Bell's palsy subjects were found in only the tympanic and mastoid measurements [6]. Multiple studies have also evaluated the facial recess as it is implicated surgically in cochlear implantation and other mastoid surgeries. A recent study by Calli *et al.* demonstrated a range of 5.6mm to 18.4mm and a mean of 7.8mm between the takeoff of the chorda tympani and the incus buttress[9]. Other objective studies of the intra-temporal facial nerve have focused on imaging features, concluding that coronal and axial sections from high resolution CT are excellent for visualization of the bony canal [10], and that various magnetic resonance (MR) techniques provide the superior soft tissue delineation needed for diagnosis of many pathologies (e.g. schwannoma, malignancy, neuritis) [11].

The incidence of iatrogenic injury of the facial nerve during mastoid surgery has been estimated to be as high as 1.7%[12]. Along the labyrinthine segment, the facial nerve is in very close proximity to the basal turn of the cochlea, ranging from 0.06 to 0.8mm, and both structures can be vulnerable during surgery[13]. Just distal to this, the geniculate ganglion has previously been shown to lack a bony covering in 15% of temporal bones [14], therefore requiring caution during middle fossa surgical approaches. Along the tympanic segment, the wall separating the nerve from the middle ear is thin and easily fractured, and in up to 33% of cases dehiscent [15], making it susceptible to pathologic processes of the middle ear, such as acute otitis media and barotrauma. Although the mastoid segment is generally predictable in orientation, and well-preserved surgically, rare anatomical variations in shape exist, such as bifurcation[10].

One promising approach to minimizing the risk of facial nerve injury has been the recent introduction of image-guided minimally invasive[16] and robotic[17] surgical approaches. Another approach has been in enhancing the training environment for training otologic surgeons, by providing a more safe and effective method of developing operative skills and spatial awareness. This is a notable challenge, as previous evidence has demonstrated a reduction in the prevalence of cholesteatoma, and therefore a reduction in total mastoidectomies performed, leaving less opportunity for trainees to develop these skills in residency[18]. To address this, there has been an emergence of virtual simulation platforms[19,20], with a recent study by Locketz *et al.* demonstrating the effectiveness of virtual simulation in improving confidence among junior learners[21].

Both the image-guided surgical techniques and virtual training environments rely on three dimensional volumes obtained from CT or MR scans. The process of segmenting these volumes is quite time-intensive if done manually. Instead, automated segmentation algorithms are now being applied in otology to evaluate the inner ear[22,23], facial nerve[24], and combined temporal bone structures[25]. These segmentation algorithms have so far used multi-atlas segmentation[25] and statistical shape modelling[23,24,26], and deep learning remains a promising method demonstrated in many other organ systems[27,28]. However, developing effective image processing algorithms often requires large datasets, and collection of many high definition temporal bone scans is a noted challenge. Two groups have recently created publicly available data sets, with eight[29] and 51 temporal bone specimens[30], respectively, although there still remains some growth necessary to achieve the statistical power needed for algorithm training and validation.

The present study will aim to expand the objective understanding of the facial nerve anatomy within the temporal bone using high-resolution micro-CT (μCT) and novel statistical shape analysis. Anatomical measurements of the nerve path will be evaluated, and regions of statistical variability in the shape of the facial nerve will be demonstrated. This study will provide statistical models for automated segmentation algorithms, and the models will be made publicly available to all researchers to foster collaborative research.

MATERIALS AND METHODS

Ethics approval was obtained from the Department of Anatomy at the Schulich School of Medicine and Dentistry. Three-dimensional μCT images were collected from 40 cadaveric specimens. Specimens were taken from 21 donors, with an even distribution of 20 right and 20 left ears. The temporal bone and its structures were removed from the body and brain for simplicity of the experimental method. The specimens were scanned using the GE Healthcare eXplore Locus μCT scanner (GE Healthcare, Chicago, IL). The scanner was operated with a voltage of 80 kV and current of 0.45 mA. Approximately 900 views were captured at an incremental angle of 0.4 degrees. Images were reconstructed with an isometric voxel size of 154μm.

The open source software Slicer v4.6.2 [31] was used to analyze the imaging data. All images were aligned using a series of rigid registration steps. To begin, one master image volume was manually rotated into the standard anatomical position to ensure that multiple landmarks, including the semicircular canals, pinna, tragus and ossicles, were correctly oriented. All left-sided temporal bones were mirrored to match the right. Image volumes were aligned to the master volume using a rigid body fiducial registration (as implemented in the Slicer platform), with fiducials centered on the following landmarks: cochlear nerve at the entry point to the cochlea, center of the oval window, and center of the round window.

A series of measurements were made in Slicer to quantify the dimensions of the facial nerve canal, a graphic representation of which can be seen in **Error! Reference source not found.**. All measurements and segmentations were reached via consensus interpretation by three authors (T.J.H., B.G., and S.K.A.) to minimize interobserver variability. Some measurements were made based on those previously described in the literature, as mentioned above, including diameters at the minimum bottlenecks of the labyrinthine and tympanic segments, and the length of each segment. For the three nerves leaving the mastoid portion - the nerve to the stapedius, chorda tympani and Arnold’s nerve (auricular branch of the vagus nerve) – the height from the stylomastoid foramen was measured. Additionally, the angle between the chorda tympani and the facial nerve was recorded, as it is representative of the facial recess. Nerve branches were not traced past the first 2-3cm, as most could not be followed reliably into the surrounding architecture. The three branches from the geniculate ganglion – the greater, lesser and external petrosal nerves – were observed but not reported in the current study, as their position showed little variability and their measurements yielded little clinical significance.

As part of the measurement analysis, an assessment of facial nerve dehiscence was also performed. Images were first visually inspected along the tympanic segment for apparent absence of bone between the fallopian canal and middle ear cavity. An example can be seen in **Error! Reference source not found.**, where there is an apparent loss of CT signal in the tympanic segment just lateral to the geniculate ganglion. Images that showed signs of dehiscence were then evaluated further, where voxel intensities along 2-4 segments travelling from the canal through the region of interest to the cavity were obtained. If at least two of the segments depicted a decrease in signal, with no spike in intensity at the interface, then the region was deemed dehiscent.

Shape variation of the facial nerve was analyzed using two different methodologies. First, a principle component analysis (PCA) was performed using mathematical calculations well described in the literature[32,33]. To perform a PCA on the facial nerve found in this dataset, 11 landmark fiducials were placed along the canal, as seen in **Error! Reference source not found.**.

Five separate sections of the nerve were analyzed – the labyrinthine, tympanic, and mastoid segments, along with the junctions at the geniculate ganglion and second genu.

The second method created a statistical shape model (SSM) with the open source modelling platform Statismo [34]. The nerve canals were initially segmented manually from the μCT data set. Within Statismo, a gaussian process model was created to determine the mean facial nerve, with the gaussian kernel setting of $\sigma = 50$ and 200 basis functions. This mean nerve was used as the reference shape, and all other facial nerves were fit to it to attain a point-to-point correspondence. With this correspondence, a statistical analysis could be performed using the platform's mathematic computation, where all of the nerves were projected onto the reference shape to determine the overall shape variability.

RESULTS

The measurements of the facial nerve canal and its branches can be seen in **Error! Reference source not found.**. A 95% confidence interval (two standard deviations) was used for all measurements. Image analysis demonstrated that nine of the 40 facial nerves (22.5%) were dehiscent in the tympanic segment. Two came from opposite ears of the same cadaver, and both demonstrated dehiscence in the tympanic segment adjacent to the oval window. The other seven came from individual cadavers, and demonstrated dehiscence just lateral to the geniculate ganglion, as demonstrated in **Error! Reference source not found.**.

The PCA performed on the 40 sets of landmark fiducials can be seen graphically in **Error! Reference source not found.**. All four images (4A to 4D) demonstrate the same mean nerve shape in yellow, and then project six more nerves according to the direction and magnitude provided by the component coefficients from the PCA calculation. Blue through red demonstrates seven shapes produced by $n\sqrt{\boldsymbol{\lambda_i}}$, where n is the index for each shape (-3 in blue, -2 in teal, -1 in green, 0 in yellow, 1 in orange, 2 in dark orange, and 3 in red) and $\boldsymbol{\lambda_i}$ is the eigenvalue for that component. The value, $\sqrt{\boldsymbol{\lambda_i}}$, was the multiplier chosen as it is a value representing the amount of statistical deviation accounted for by that component, analogous to standard deviations in a gaussian distribution. Note that these are constant diameter representations and do not capture the true diameters along the nerve.

Although PCA does discover numerous modes of variation in complex data, most of the shape variability in this analysis came from the first four components, accounting for 75.3% of the net variation. Here, the first component in the superior/inferior distribution (Figure 4A) appeared to capture variability just proximal to the second genu, angling the tympanic segment from inferior to slightly superior in the extrema. The next three components appeared to capture variability primarily in the mastoid segment, where anteromedial/posterolateral (Figure 4B), medial/lateral (Figure 4C), and anterolateral/posteromedial (Figure 4D) distributions were seen.

Error! Reference source not found. shows all the component surfaces combined into one view, helping to illustrate the major regions of variability. The labyrinthine segment, geniculate ganglion and proximal tympanic segment remained relatively fixed, with the overall shape preserved and up to 2-3 millimeters of translation. The first major variation was found in the distal tympanic segment, as described above in the first principle component and seen again in **Error! Reference source not found.**A (violet), where the slope angled from inferior to slightly superior in the extrema. The most variability, however, occurred in the distal mastoid segment and stylomastoid foramen, as seen most clearly in Figure 5B. Here, the second and third components (green and blue, respectively) demonstrated a strong tendency for the nerve to vary along their anteromedial/posterolateral and medial/lateral axes. The perpendicular axes demonstrated in components one and four (violet and orange) showed significantly less variation, and it can therefore be inferred that the possible locations of the stylomastoid foramen relative to the temporal bone varies in a cross distribution (seen graphically in **Error! Reference source not found.**B).

The SSM created with the Statismo framework demonstrated similar variability patterns as described above in the PCA. Components one through four of the SSM can be seen in **Error! Reference source not found.**(A)-(D). Component one of the SSM (**Error! Reference source not found.**A) demonstrated a close match to the first component of the previous PCA (**Error! Reference source not found.**A), showing a change in superior/inferior angulation of the tympanic segment, along with a moderate amount of anterior/posterior translation of the mastoid segment. Component two of the SSM (**Error! Reference source not found.**B) demonstrated an isolated variation in the superior/inferior length of the mastoid segment, a change seen partially in each of the first, third and fourth components (**Error! Reference source not found.**A, 4C, 4D, respectively) of the PCA. Component three of the SSM (**Error! Reference source not found.**C) demonstrated a similar medial/lateral displacement of the mastoid as the second component of the PCA (**Error! Reference source not found.**B), along with some translation of the labyrinthine segment, as seen through all previous components. Component four of the SSM (**Error! Reference source not found.**D) also demonstrated the anterior/posterior displacement of the mastoid segment as seen previously in the PCA. In summary, the anterior/posterior translation of the labyrinthine segment, the superior/inferior angulation of the tympanic, and the anterior/posterior, medial/lateral and superior/inferior displacements of the mastoid segment were re-demonstrated in the Statismo SSM.

One additional observation of the facial nerve was made from processing the imaging data, where the fallopian canal appeared to split into two at the second genu, and the facial nerve appeared to travel in two separate canals inferiorly through the mastoid bone. This was found in two of the 40 facial nerves (5%), from separate cadavers.

DISCUSSION

Many of the quantities measured in this analysis were comparable to those found previously in the literature. Regarding the minimum diameters of the labyrinthine and tympanic segments (the bottlenecks), there was close agreement between those found in the current study and in a previous study by Nakashima et al. [8] (0.91 and 0.94mm compared to 0.89 and 0.92mm, respectively). Regarding lengths, reports from an early CT study [5] demonstrated ranges 2-6mm, 8-11mm, and 9-16mm which were comparable to the 2.11-5.36mm, 7.73-12.91mm, and 11.09-19.63mm measurements found in the current study for labyrinthine, tympanic and mastoid segments, respectively. The ranges reported in the current study, however, were influenced by a small portion of outliers, and the overall mean and standard deviation tends to fit well within the previously reported ranges. Regarding dehiscence, the 22.5% reported in the current study is lower than the 33% quoted in a recent study [15], although a past compilation of surgical study data demonstrated that dehiscence is present in 25% of cases on gross dissection, and can range from 6-33% on histology [35].

The use of μCT technology permitted several additional observations from what was found in the literature. The greater and lesser petrosal nerves were able to be reliably traced anteriorly to the meeting point with the deep petrosal and tympanic plexus branches, respectively. The external petrosal was a very thin branch, had the greatest degree of variation projecting in nearly any direction, and was not identifiable in three of the specimens. This was not surprising, as previous anatomical literature has cited that the external petrosal is an inconstant branch, in some instances joining the greater and lesser petrosal nerves directly from the carotid canal[36]. Of the three branches exiting from the mastoid segment, the chorda tympani had the greatest variation in its exit height. Although this height has not been directly reported previously, the standard deviation of 2.33mm is comparable to the deviation of 2.68mm reported for the facial recess width in the literature [9]. Additionally, the same study demonstrated a recess angle of 23.58±6.84°, which matches closely the angle of 23.5±24.0° reported in the present study (note that the previous study reported a confidence interval of one standard deviation, while the present study reports two standard deviations). The nerve to the stapedius was the most predictable branch, and subjectively was almost always found branching antero-medially just below the second genu.

The statistical shape analysis added a new perspective to the study of the facial nerve, demonstrating the statistical distribution of nerve paths through the temporal bone. As mentioned, there were two areas with significant deviation: the first being at the distal tympanic segment, with variation on one statistical plane showing a superior to inferior change in angulation; the second being at the distal mastoid segment, with variation primarily along two statistical planes. Otherwise, nerve shape was relatively constant and only varied in position by approximately 2 to 3mm. From a surgical point of view, this distal tympanic site is of particular significance, as a recent case study has demonstrated that the intratympanic facial nerve is commonly injured around the tympanic segment and second genu[37]. Iatrogenic facial nerve injury is a devastating complication of otologic surgery, and the reported incidence rate of 1.7%[12] could potentially be minimized through anatomic knowledge, surgical experience, nerve monitoring, and image guidance.

One source of error in the current study was due to the process of manually selecting landmarks. Extensive image segmentation studies in the literature have demonstrated that inter-observer variability can be an issue in image identification. This was mitigated in the present study through consensus interpretation by multiple observers, and through the use of high-resolution images, which clearly delineated borders and areas of interest. Another potential source of error arose from the fiducials chosen for the initial rigid registration. The images were all aligned such that the three fiducials chosen – the cochlear nerve, the oval window, and the round window – were always in approximately the same position. Small variations in the true orientation may have influenced the variability in the models demonstrated; however, substantial portions of the nerve, including the proximal mastoid and tympanic segments, had little shape variability, therefore this likely had a minor effect. Furthermore, the agreement of these results with those found in previous studies supports that the methods used here produced results within reasonable limits.

Several studies have previously attempted to characterize features of the facial nerve path, including diameters, lengths and presence of dehiscence. This study aimed to expand on this knowledge through a cadaveric imaging analysis using μCT images, providing size measurements and adding new information about angulation, branching and dehiscence. Additionally, this study was the first to use a μCT dataset to create a PCA and SSM of the facial nerve, demonstrating in three dimensions how the facial nerve varies within the temporal bone. Along with providing valuable knowledge of the anatomy, the data processing and statistical models created here will be further used in the development of automatic segmentation algorithms. The images, data and models will be made available to the greater research community via the Auditory Biophysics Laboratory website (abl.uwo.ca).

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FIGURE LEGENDS

Figure 1 – Three-dimensional and CT representations of the intratemporal portion of the facial nerve. Figures A, C, and E demonstrate spatial orientation of the nerve (yellow) relative to the vestibulocochlear system (blue), ossicles (white), and stapedius muscle (red). Figures A and B demonstrate an axial view of the labyrinthine segment, with the vestibular, cochlear and facial nerves entering from the internal auditory canal. Figures C and D demonstrate a parasagittal view of the tympanic segment, with the nerve deep to the ossicles and near the semicircular canals. Figures E and F demonstrate the mastoid segment, with a clear view of the facial recess between the mastoid segment and the chorda tympani.

Figure 2 – Dehiscence between the facial canal and the middle ear cavity just lateral to the geniculate ganglion in one subject (A) on axial view, and a thin but intact bony separation in another (B). Dotted segments drawn in (A) were used to measure for a spike in intensity at the interface, implying presence or absence of bone.

Figure 3 – Graphical representation of the diameters, lengths and angles of the facial nerve canal. L, D, h and θ represent the length, diameter, height and angle. Subscripts L, T, and M denote the labyrinthine, tympanic and mastoid segments, and subscripts 1 & 2 denote the first and second genu. Nerve to stapedius, Arnold's nerve and Chorda tympani (NS, AN, CT) were defined by their height above the stylomastoid foramen, along with the angle with the angle between the chorda tympani and the facial nerve (representing the facial recess). A 95% confidence interval was reported (two standard deviations).

Figure 4 – Principle components 1-4 (A-Superior/Inferior, B-Anteromedial/Posterolateral, C-Medial/Lateral, D-Anterolateral/Posteromedial). Yellow surface represents the mean shape, with

three additional surfaces in each direction demonstrating $\pm 1\sqrt{(\lambda_i)}$, $\pm 2\sqrt{(\lambda_i)}$, $\pm 3\sqrt{(\lambda_i)}$ in variation. Cardinal directions for all figures demonstrated in A (Superior (S), Inferior (I), Anterior (A), Posterior (P), Medial (M), Lateral (L)).

Figure 5 – All principle component surfaces from above, in diagonal (A) and axial view (from inferior). Component 1 shown in violet (superior/inferior), 2 in green (anteromedial/posterolateral), 3 in blue (medial/lateral), 4 in orange (anterolateral/posteromedial). Dotted red line demonstrates the cross distribution of the stylomastoid foramen.

Figure 6 – Statistical shape model produced by the Statismo framework. This representation demonstrates the variability of components 1-4 (A = superior/inferior, B = anteromedial/posterolateral, C = medial/lateral, D = anterolateral/posteromedial) by showing facial nerves with +/- 2 standard deviations along each component and the distance (arrows) from points to their corresponding points on the mean facial nerve. Larger arrows and color approaching the red portion of the spectrum demonstrate regions of increased variability.