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Influence of middle ear tumours on the biomechanical behaviour of the chorda tympani

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Abstract

Chronic otitis media may lead to the development of a cholesteatoma, a benign middle ear tumour. If this occurs, the chorda tympani nerve, a facial nerve branch that crosses the middle ear, may be compromised. The influence of cholesteatoma development near chorda tympani nerve was studied, in order to assess the consequences of this mass in terms of possible facial paralysis. To do so, an ear model based on the finite element method was used. The chorda tympani nerve was originally discretized and assembled in the model. Two different sized tumours were created so cholesteatoma growth could be simulated. The pressure in this nerve were assessed in two moments - when the tumour first interacts with it, pushing it down, and when the tumour compresses it against the incus. Moreover, the effect of applying pressure directly on the nerve was also evaluated, so tumour geometry did not interfere in the analysis. The obtained stress allowed to infer on the consequences regarding taste disturbance and facial paralysis, although some studies report that when pressure fades away, it is possible to fully recover. The von Mises stress was higher when the chorda tympani nerve was pushed against the incus by the large tumour, in the contact area between the nerve and the ossicle.

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1. Introduction

Chorda tympani nerve (CTN) is a nerve that arises from the facial nerve and crosses the tympanic cavity between the malleus and the incus. The course of CTN can be divided into three portions, as it is shown in Fig. 1, connecting the facial to the lingual nerve [1, 2]. CTN provides parasympathetic innervation to submandibular and sublingual glands as well as special sensory taste fibres for the anterior two thirds of the tongue, through the lingual nerve, being this way related to saliva secretion and taste sensation [3, 4]. As there is no cover involving the CTN, this structure is highly vulnerable to the events that happen in its surroundings [5, 6].

Some studies to better understand the CTN have been conducted over time. CTN was described in literature as having a diameter between 0.3 and 0.5 mm, showing wide inter patient variation [7]. In order to have a better surgery outcome, Liu et al. studied the whole course of some deep nerves in human head [2]. Regarding CTN, the values for the part that crosses the tympanic cavity were a diameter around 0.44 mm and a length of 9.83 ± 1.24 mm.

Otitis media (OM) is a middle ear infection that can either occur as an acute otitis media or, if it lasts longer than three months, as a chronic otitis media (COM). The latter may lead to tumour development, being cholesteatoma the most common tumour that occurs as a consequence of a COM. Cholesteatomas are middle ear benign tumours, characterized for being pouch like lesions and resulting from accumulations of skin debris [8].Cholesteatomas may affect the surrounding structures as it grows, as it can trigger an inflammatory reaction, which leads to the appearance of osteoclasts, that are capable of destroying bone cells [9, 10], leading to ossicular chain erosion. Moreover, if the tumour grows in such a site that pressures the CTN, it can affect this nerve's function, which can ultimately result in facial palsy (FP), the inability to move a part of the face.

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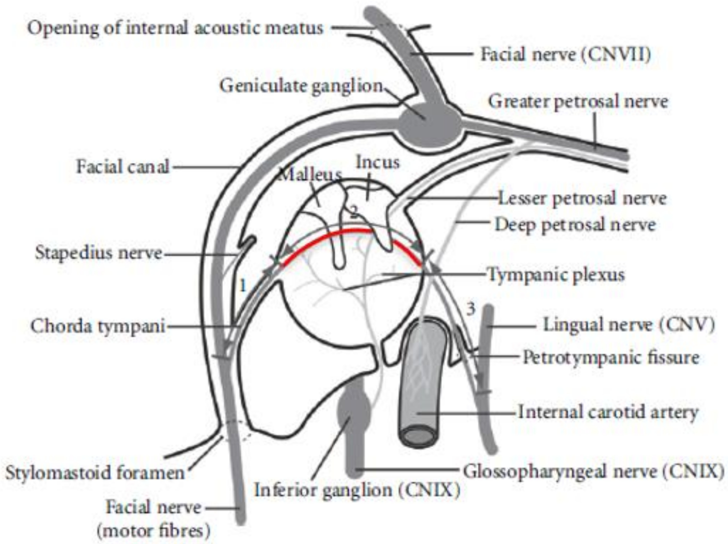

Fig. 1 - CTN portions between the facial nerve and the lingual nerve. Portion 1: mastoid process, portion 2: tympanic cavity, portion 3: submandibular fossa [2].

Former studies show that there is a close connection between pressure and the induction of osteoclastic bone resorption that is typically associated to cholesteatomas. Thus, Orisek and Chole conducted a research on the pressure exerted by cholesteatomas on nearby structures [11]. The results pointed to pressures between 1.31 and 11.88 mm Hg, equivalent to 174 and 1 584 Pa respectively, being the ones that lead to greater osteoclastic activity.

The link between FP and OM and cholesteatoma was also a matter of interest. Takahashi et al. (1985) conducted a study to assess this connection, concluding that FP caused by COM usually occurred together with cholesteatoma or acute increase of inflammation in the middle ear, being the paralysis mild and its progression slow. Savic and Djeric (1989) conducted a study including 1 261 patients that were subjected to a surgery due to COM. Of all these patients, 64 showed FP before surgical intervention, being a cholesteatoma present in 52 (80%) of these cases. This suggests that FP is highly connected to cholesteatoma following COM. After surgery, complete recovery was managed in 45 (70%) of the patients [12]. Thus, surgery can be considered an efficient approach to restore facial function. In 2001, Hu and Wang studied the connection between CTN and cholesteatoma development in its surroundings, concluding that cholesteatoma leads to ultrastructural changes of the CTN [13]. In 2007, Clark and O'Malley studied the influence of iatrogenic CTN injuries [14]. The results suggest that cholesteatoma leads to damages in CTN, as patients with cholesteatoma show less symptoms alteration after nerve injury during surgery, which indicates that the tumour leads to CTN hypofunctioning.

Patients that suffer from FP due to the pressure exerted by a cholesteatoma usually recover the facial functions after cholesteatoma removal, as the pressure on the nerve vanishes. The time period for this recovery can go up to some months. However, if for some reason the cholesteatoma causes irreparable damages in the nerve, facial function may never return to normal. The most critical period when referring to cholesteatoma recurrence are the first two years after surgery, as most reported cases happen during this term [9]. Recurrence of 26.9% was obtained in a study conducted by Syms and Luxford in 2003 [15]. Thus, the aim of this work was to evaluate the influence of cholesteatoma size in the CTN pressure, which could lead to FP.

2. Methods

The Finite Element Method was used as discretization technique in the current study, being FEMAP© and ABAQUS© the used software, the first used to model the cholesteatomas and the CTN and the latter to run the simulations [16]. Two different sized tumours were built and assembled to the middle ear model, in the connection between the malleus and the incus, as the development of a tumour in this location would affect CTN [17]. The geometries had an ellipsoid shape, considering that the smaller one should reach the CTN area only from above and the bigger one should be large enough to partially wrap the CTN, so the effects of the tumour compressing the nerve against the incus could be tested. According to Raveh Tilleman et al., that studied cancerous tissue mechanical properties, this tissue Poisson's ratio is 0.43±0.12 and the Young's modulus is, on average, 52 kPa [18]. Therefore, an elastic behaviour considering these values was defined for the cholesteatomas. CTN was then modelled, improving the existing middle ear model. This structure was originally modelled in the present work and incorporated in the computational model.

According to the previously mentioned values obtained by Liu et al., and supported by the description of the nerve course, it was possible to create a reliable computational representation of the CTN [2]. The modelled CTN had the diameter reported by Liu et al., 0.44 mm, and its length was slightly higher, as the nerve had to be adjusted to the structures present in the used middle ear model, being its value 13.3 mm.

The mesh was created, being composed of 2875 nodes and 2052 C3D8 elements. Due to scarce information regarding CTN properties, the Poisson's coefficient and the Young's modulus assigned to this structure were based on a study regarding the mechanical properties of the sciatic nerve, conducted by Liu et al., being 0.37 and 4.1×10^7 N/m^2, respectively [19]. After modelling and meshing the CTN in the appropriate position, this structure was properly adjusted to the ossicles and the simulations were performed. The main goal was to understand the behaviour of the CTN when pressured by a cholesteatoma. Thus, the simulations were performed considering that the CTN would be initially pushed down and then, as the tumour grows, pushed against the incus. As the idea was to simulate the pressure exerted by the cholesteatoma growth, an internal pressure was defined to simulate it. Thus, a shell with the tumour shape was created and connected to the ossicles.

The first simulations were made with the smaller tumour, with an associated pressure of 174 Pa, corresponding to the lower value obtained by Orisek and Chole. This way, this pressure was applied in the internal surface of the shell [11]. The CTN was fixed in its extremities and the ossicles were totally immobilized. The part of the shell connected to the ossicles was also fixed. The von Mises stress was analysed in three different nodes of the CTN, as showed in Fig. 2. The chosen nodes were X, a central node in the part of the CTN that is pushed down in the first interaction between the CTN and the cholesteatoma, Y, a central node in the section of CTN that contacts with the incus, on the side on which the cholesteatoma would apply pressure, and Z, not visible in the representation, a central node in the part of the CTN that would be pressed against the incus, in the opposite side of Y.

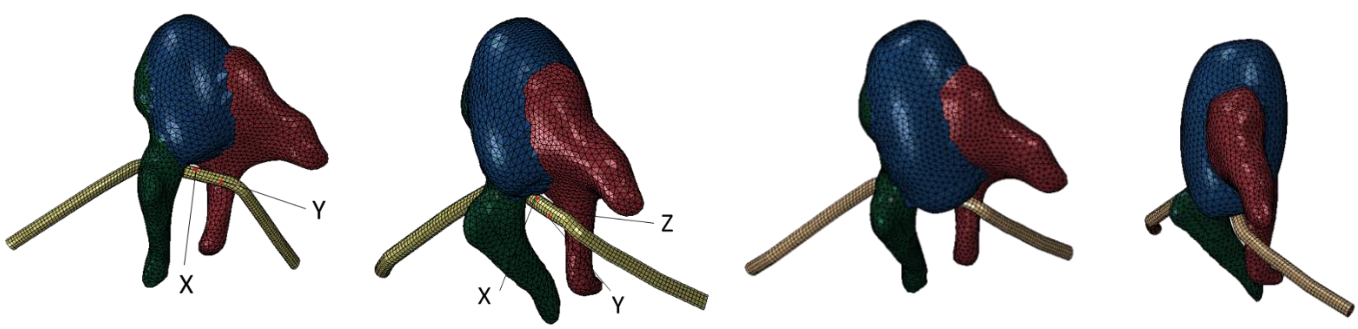

Fig. 2 - CTN (yellow) and small (left) and large (right) cholesteatomas (blue) in the middle ear. X, Y and Z are nodes in which the results of applying pressure on CTN were assessed. Green ossicle: malleus, red ossicle: incus.

Then, the interaction between the CTN and the large tumour was studied. The same procedure was applied for the large tumour. Instead of applying an internal pressure of 174 Pa, a higher value in the pressure interval described in the work of Orisek and Chole (174 – 1 584 Pa) was used. As it is a large tumour, but it can still grow and be capable of exerting higher pressures on the surrounding structures, the chosen value for this simulation was 1 300 Pa. The results were analysed in the same nodes. In order to better evaluate the effect of compressing CTN against the incus, an additional simulation was performed. This way, a pressure was applied directly in the CTN, in order to simulate the effect of the tumour. The used values of pressure were the same as in the previous simulations, 174 and 1 300 Pa, being the results analysed for the two nodes close to the incus, Y and Z.

3. Results

The von Mises stresses were analysed and compared for the three different mentioned locations. The influence of the tumours growth was analysed and then the effects of applying pressure directly on the CTN were also evaluated. Initially, this was tested by expanding the tumours towards the CTN. The effects of applying an internal pressure of 174 Pa on the small tumour shell were assessed. Table 1 shows the von Mises stress obtained for nodes X, Y and Z and Fig. 3 the stress distribution on CTN.

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Table 1 – von Mises stress obtained for the CTN when affected by the cholesteatomas.

Nodes	X	Y	Z
von Mises stress for small tumor (Pa)	94699	217012	334652
von Mises stress for large tumor (Pa)	89064	181840	404098

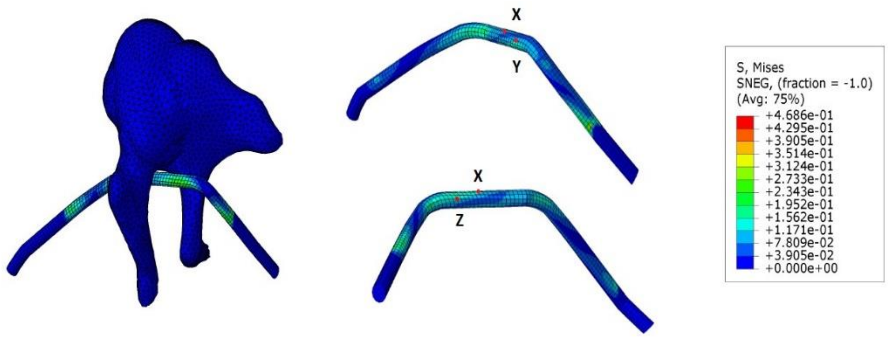

Fig. 3 – von Mises stress obtained for the CTN when affected by the small tumour.

The large tumour influence on CTN was then studied. Table 1 shows the von Mises stress obtained for the three nodes, for a pressure of 1 300 Pa. In Fig. 4 it is possible to observe the stress distribution on CTN.

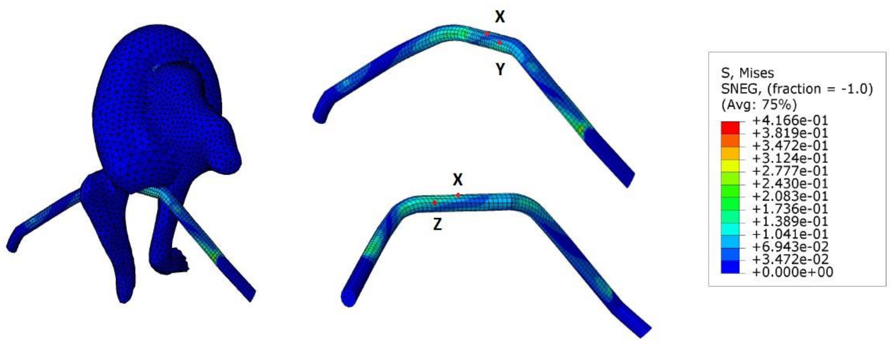

Fig. 4 – von Mises stress obtained for the CTN when affected by the large tumour.

Finally, the effect of applying a pressure directly on the CTN surface was studied, being the results in Table 2.

Table 2 – von Mises stress obtained for the CTN when pressure is directly applied on its surface.

Nodes	Y	Z
von Mises stress (Pa) for an applied pressure of 174 Pa	217017	337067
von Mises stress (Pa) for an applied pressure of 1300 Pa	217054	352899

4. Discussion

The hypothesis considered in the present work was the influence of cholesteatoma size in the CTN stress. The results showed that the cholesteatoma size seems to have influence in the CTN stress only when it contacts with a stiffer structure as the incus and couldn´t move.

In what concerns the simulations related to the small tumour, it is possible to observe that the higher stress value occurs for the node that contacts with the incus, Z. Although node X is closer to the pressure source, the cholesteatoma, this part of the CTN can move freely without any other structure blocking its movement. This way, the higher stresses will be related to the node that contacts with the incus, as this ossicle blocks CTN movement.

It is possible to observe that, regarding the large tumour, the highest stress value occurs, once again, for the node in contact with the incus. In general, it would be expected that the stress values concerning the large tumour were higher than the ones obtained for the smaller one, which does not happen. Nevertheless, it is important to take into consideration that the tumour shape may have influence. This way, and as the large tumor had to be adjusted to the CTN, its lower face is not flat as it is the one of the smaller tumour. The irregularity of the large tumour lower surface may be the reason why

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the applied internal pressure does not lead to higher stresses. The differences in the cholesteatoma shape outline should be considered in a further research, as it could influence the results. However, the von Mises stress values obtained in the node Z, which is the node with the same conditions in both simulations (pressured against the incus) showed the higher difference between both tumours, with higher stress for the large tumour. This should be considered the most relevant analysis in the present work, as the FP has higher probability to occur when the CTN is pressured to a stiffer structure.

By applying pressure directly on the CTN, it is possible to observe that the stress is higher when a higher pressure is applied, being this difference more relevant in node Z, the node that contacts directly with the incus. This may be explained by the fact that this node has a fixed barrier to stop its movement, the incus, which causes a higher stress on the CTN.

It is possible to observe that node Z is the one with higher stress in all the performed simulations, which is expected as this is the node that contacts directly with the incus. For the simulations using the developed cholesteatomas, the stress associated to the large tumour was around 20% higher than the stress in the case where the small tumour effects were analysed.

As no former studies were found regarding this topic, it was not possible to compare these results with literature values. Thus, the obtained results only allow to infer on possible outcomes for CTN damage, as cholesteatoma continues to grow. As CTN crosses the middle ear close to the ossicles, tumour growth near this structure will probably permanently damage the CTN by compression against one of the ossicles, leading to higher stress in CTN. Being compressed by the cholesteatoma against the incus may lead to highly taste distortion and, eventually, FP, if the pressure on CTN is high. Nevertheless, several studies suggest that these symptoms are likely to disappear when pressure fades away. Furthermore, it was possible to conclude that a cholesteatoma that grows in the same site as the one simulated in this work starts to directly interfere with CTN from the moment it has a dimension slightly superior to the smaller tumour.

5. Conclusion

The results suggest that the fact that the CTN runs uncovered in the middle ear makes it more susceptible to be damaged by any unexpected body that can grow nearby.

Node Z is the one that records higher stresses in all cases, with an increase of around 20% for the larger tumour in the first simulations. The obtained stresses show that the fact that CTN is positioned between two ossicles, it increases the possibility of permanently damage by compression it against a fixed and stiffer structure. This allows taste disturbance and, possibly, facial paralysis.

Nomenclature	
CTN	*Chorda tympani nerve*
OM	*Otitis media*
COM	*Chronic otitis media*
FP	*Facial palsy*

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