A Middle-Ear Finite-Element Model

The tympanic membrane (TM), including pars flaccida and pars tensa, was clamped at its anterior-mallear ligament (AML), superior-mallear ligament (SML), and tensor tympani muscle (TTM), as these structures are considered because of their assumed rigidity. (T); SAL YM (Y), IMJ YM (Y), ISJ YM (Y), and YM of remaining ligaments (Y); pars flaccida YM (Y) and thickness (T).

The OA L (2 ) (Taguchi, 1987) is shown in Table 2. It represents 15 two-level parameters, and a total of 16 simulations.

- Young’s modulus
- Poisson’s ratio
- Thickness

The complete model includes 2015 nodes and 6115 triangle shell elements. The finite-element simulations are done with SAP98 (Bathe et al., 1974).

The complete model was tested for static loading, corresponding to frequencies low enough that inertial and damping effects can be neglected. The response of the individual node was measured using laser Doppler vibrometry of Dalhousie University. The simulated displacement for the TM with 2% of the experimentally measured values, and the amplitudedispacement for the shapes is 1/3 of the measured value. This is close enough to serve as the basis for an exploration of the effects of parameter variations.

### Results

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A 3-D finite-element model of a human middle ear was generated based on the three-dimensional geometrical data from a middle-ear specimen and the corresponding image-segmentation process due to limited spatial resolution and contrast. Likewise, uncertainty in the choice of middle-ear properties parameter values can arise from limited spatial resolution and contrast. Nevertheless, uncertainty in the choice of middle-ear properties parameter values can arise from lack of relevant measurements, from ear-to-ear variability, etc.

One-factor-at-a-time sensitivity analysis is commonly used to study the effects of parameter variations; however, it does not take into account the possibility of interactions among parameters which can affect model behaviour. Such interactions mean that the model response to one parameter is not the same for all parameter values. Alternatively, the full-factorial method permits the analysis of parameter interactions and generally requires an excessive number of simulations. A more practical alternative is the Taguchi method which was developed primarily for industrial design. Via orthogonal matrices and analysis of variances (ANOVA), it determines the relative importance of each parameter and identifies interaction among them.

#### Methods

The procedure for applying the Taguchi method as follows:

1. **Step 1:** Select parameters and interactions of interest.
2. **Step 2:** Select parameter levels.
3. **Step 3:** Find a suitable OA with the smallest number of runs. This normally involves sorting up a predefined OA based on the number of parameters, interactions and levels.
4. **Step 4:** Map the factors and values to the OA.
5. **Step 5:** Run simulations based on the OA.
6. **Step 6:** Analyze simulation results.

The OA is shown in Table 2. Each parameter's levels are represented by +1 or -1 levels, and the OA is balanced in terms of orthogonality and uniformity.

### Discussion

We observed that a strong interaction exists between the Young’s modulus of the incudomallear joint and the tensor tympani muscle. It is important to take into account when the parameter effects on model behaviour are being considered. It will be interesting to extend the analysis to include more parameter levels, ears, and interactions.

### Conclusions

This is the first time that interactions between parameters in a middle-ear finite-element model have been studied.

The Taguchi method is an efficient and effective method for investigating parameter sensitivity and interactions.

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### References