Functional inoperability of oral and oropharyngeal cancer

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Chapter 8

Development of a dynamic model of the tongue for virtual surgery.

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ABSTRACT

Purpose. Advanced oral cancer can be treated by surgery or chemoradiation. This paper describes the development of a dynamic 3 dimensional (3D) model of the tongue. This is the first step in developing a model of the oral cavity and the oropharynx to allow virtual resection. The goal is to enable preoperative assessment of postoperative function, contributing to a better treatment choice.

Methods. The finite element method is chosen to model the tongue. A 3D geometrical model of the tongue, consisting of 480 elements, is obtained by segmenting a multi resonance image (MRI). Models of the individual tongue muscles are placed according to anatomical descriptions and are activated manually.

Results. A FE model of the tongue is developed. The model shows expected tongue movements by the activation of separate of combined muscle groups. By changing stiffness parameters it is possible to mimic other tissue types, like scarring effects caused by surgery or radiotherapy. Volume changes are found during movement in individual elements, ranging from 74% to 129%. The volume of the total tongue body shows smaller volume changes; 99% after activation of the posterior part of the genioglossal muscle to 112% after activation of the superior longitudinal muscle. At the end of the movement, volume change of the whole tongue is small, on average 103%.

Conclusion. The first steps in the development of a FE model of the tongue have been taken. Refinement is necessary to make the model suitable for future virtual surgery applications.
INTRODUCTION

Surgery, frequently combined with adjuvant radiotherapy, is the mainstay for treatment of oral cancer. However, oral surgery might seriously interfere with speech, swallowing, and mastication, especially in advanced cases. An alternative for surgery in the treatment of advanced head and neck cancer, is organ-sparing therapy, consisting of concurrent chemoradiotherapy (CRT), which has become more common in recent decades. Both treatment regimes, surgery and CRT, result in comparable survival rates, which makes it important to assess the functional consequences of each modality carefully.

After CRT, patients may suffer from dysphagia, due to fibrosis and xerostomia, depending on the radiation dose and tumour location. Apart from patient-related factors, like age and comorbidity, function losses after surgery are mainly dependent on the location and extension of the tumour as these define the amount of tissue that should be removed in order to achieve clear margins. The choice between surgery and CRT remains difficult in certain cases and requires a careful weighing of all patient- and tumour-related factors. The term functional inoperability, can be applied if tumour resection causes unacceptable function loss. It is currently used in clinical decision-making and indicates the irreversible function losses of swallowing and speech after surgery. In a web-based survey among head and neck surgeons worldwide, we clearly demonstrated that opinions about functional inoperability vary significantly among individual physicians. The majority of surgeons based their decision between surgery and CRT on the expected postoperative swallowing ability, loss of speech, and wishes and expectations of the patient.

In this era of evidence based medicine, clinical decisions should be based on integrating clinical expertise, best available evidence, and patient values. The integration of these three elements increases the potential for positive health outcomes.

In order to achieve an objective way of estimating the operability and to involve the patient more in the decision-making process, the expected functional loss of the oral cavity should be assessed with a higher degree of predictability. Therefore, we aim to develop a realistic dynamic 3 dimensional (3D) representation of the oral cavity to perform virtual surgery and visualise the functional impairments after treatment. In order to build such a predictive system the following items should be implemented:

- A patient-specific biomechanical/geometrical model of the tongue and the lips, including the muscular and neural systems.
- An electromyographic (EMG) muscular innervation model for the tongue and the lips.
- A biomechanical model for scar tissue.
- A virtual surgery module that adapts the models according to the planned intervention.
- A system that simulates the corresponding pathologic speech and swallowing.

The goal of the current paper is to describe the first steps taken to implement the first item, a biomechanical model of the tongue, which will make it possible to perform virtual surgical interventions.

METHODS

Cine magnetic resonance imaging (MRI) data were used from a study performed on automatic segmentation to extract the tongue geometry.\textsuperscript{14} Image sequences were captured in the sagittal and transverse plane using a 3-T MRI unit (Achieva, Philips, Best, the Netherlands). A mildly T2 weighted single-shot turbo spin echo (TSE) technique was used with a repetition time of 800 ms (per acquisition slice) as well as the following parameters: echo time 44 ms, field of view 230x122 mm\textsuperscript{2}, slice thickness 5mm, pixels size acquisition 1.8 x 2.0 mm, reconstruction 0.6 mm\textsuperscript{2}, number of signal averages 1, flip angle 90, linear profile order, refocusing 120°, sense factor 2, half scan 0.6, TSE factor 37. The MR images were loaded into Matlab 7.13.0 (R2011b), The MathWorks Inc., Natic, MA, 2011, which is also used for further development of the model.

The finite element (FE) method was used to create the tongue model. In a FE model of the tongue, the tongue is divided into several ‘brick’ elements. The muscles are located between the vertices of those elements. Deformation and movement of the individual elements, caused by the forces generated by the activated muscles, were calculated using the second law of Newton:

$$Ma + Cv + Kd = F \quad (1)$$

\(M, C \) and \(K\) represent the material properties mass, damping, and stiffness matrix, respectively \(a, v, \) and \(d\) are the acceleration, velocity, and displacement vectors. \(F\) is the force vector acting on the elements. By changing the material properties of individual elements, the effects of virtual interventions can be simulated.

The geometric information for the tongue model is obtained by segmenting the tongue from the MRI scans. The midsagittal slice was selected and segmented, as well as four slices on one lateral side, in equal steps of 4 mm from the midline. Assuming the tongue is symmetric, the contralateral side is mirrored from the segmented side, resulting in a total of nine slices. For the meshing of the tongue volume, the model of Dang and Honda\textsuperscript{15} was mimicked, with six elements in the anterior-posterior direction, and ten elements along the surface of the tongue. In total
A dynamic model of the tongue

480 3D solid quadrilateral elements were created. When the meshing process was finished, the muscle fibers of four extrinsic (genioglossal (GG), hyoglossal (HG), styloglossal (SG), and palatoglossal (PG)) and intrinsic (transversal (TRA), vertical (VER), superior longitudinal (SL), and inferior longitudinal (IL)) muscles were implemented. The GG is divided in a posterior (GGP), middle (GGM), and anterior (GGA) part. Those parts are activated individually. The muscle locations are based on the descriptions of Takemoto. In figure 1 the musculature, as situated in the model, is visualised. Activation of the muscles generates forces in the direction along the muscle fibers. The muscle activation patterns were set manually. In this way the deformation, caused by specific muscle contractions, can be analysed carefully. The strength of a contraction is also set manually.

To retrieve a unique solution from equation 1, some displacements should be identified. In the current model, the nodes on the jaw and the hyoid are fixed, meaning that displacements, in all directions, are kept zero. The geometry of the jaw and hyoid, and their positioning relative to the tongue, are also obtained by segmenting the MR images. It is not currently possible to obtain quantitative values concerning the movement of the tongue, based on specific muscle activation patterns. Another value that could be measured is the volume of the tongue. The tongue is considered as a muscular hydrostat, a muscular organ which lacks skeletal support. One of the main biomechanical features of a muscular hydrostat is the incompressibility.

Therefore we measure the volume, to verify whether the model is indeed incompressible. The Poisson’s ratio (n) is set to 0.49. This is a measure for the strain in the perpendicular directions due to an axial force in one direction. A ratio of 0.5 means a perfect incompressible material and 0 represents almost no strain in the perpendicular directions. However, it is not possible...
to use 0.5 exactly due to mathematical limitations.\(^\text{18}\) In this model, the volume changes during movement are also measured to verify whether the model is indeed incompressible.

To test whether the effects of scar tissue could be mimicked, the stiffness parameter is changed for several elements. Currently no reliable values are available for stiffness of scar tissue, and an increased stiffness (multiplied by eight) was used to mimic the effect of scar tissue formation.

**RESULTS**

**Figure 2: Results of tongue deformation**

![Image of tongue deformation](image)

Activation of individual extrinsic and intrinsic tongue muscles in finite element model of the tongue. GGM: middle genioglossal muscle, VER: vertical intrinsic tongue muscle, SG: styloglossal muscle, SL: superior longitudinal intrinsic tongue muscle

**Figure 3: Protrusion of the tongue**

![Image of tongue protrusion](image)

Activation of the transversal intrinsic tongue muscle, vertical intrinsic tongue muscle, middle and posterior genioglossal muscle.
Based on the FE method, a first, coarse tongue model was created, which is controlled manually. For some individual muscles the deformations are presented in Figure 2. A combined contraction of TRA, VER, GGP and GGM resulted in a protrusion of the tongue, as can be seen in figure 3. In figure 4 the x-, y-, and z-displacements of the tongue tip over time are shown for activation of protrusion. The activation of the muscles started at 0.01 seconds and increased linearly to the maximal activation level at 0.15 seconds. The x-displacements represent an anterior-posterior displacement, with positive values for the posterior direction, the y-displacement represents a cranial-caudal displacement, with positive values for the caudal direction, and the lateral movement is reflected by the z-displacement, with positive values for a movement to the left. As can be seen in figure 4, anterior and caudal movement is described for the movement of the tongue tip. Where the tongue is modeled in an exact symmetrical manner, no lateral movement is seen with this bilateral activation.

An average volume change of 103.1% (SD = 4.6%) was observed when individual muscles were activated. The maximal volume increment, seen after activating the SL muscle, was 112.3%, and the maximal volume decrement, found for the GGP, was 99.3%. The force applied by the muscles is chosen in such a way that a realistic deformation is seen. The amount of force influences the
volume change directly. It can be assumed that applying larger forces will result in larger volume changes. The volume changes per element can be much larger, ranging from 73.5% (SD=32.5) to 129.2% (SD = 29.7) of the original volume. However, their averaged differences in size is in all cases, except for the VER and GGP, nearer to the 100% than the total volume, with an average of 101.06% (SD = 2.0). Thus, the smaller elements change more in volume than the larger elements. The volume of the tongue body, at the end stage of the movement was 100.0% of the original volume after activation of the VER, and 99.3% after activation of the GGP. In figure 5 the volume of the tongue body in time is shown for the combined activation of the TRA, VER, GGP, and GGM muscles. At the start of the movement a small volume decrease can be seen. When the activation is held for a longer period, and the muscle force is increased, a growth in volume is seen, with a constant equilibrium of 108.8% of the original volume.

Figure 5: Volume change of the tongue during protrusion

Percentage of original volume over time for combined activation of transversal intrinsic tongue muscle, vertical intrinsic tongue muscle, middle and posterior genioglossal tongue muscle

After increasing the stiffness of several elements, the movement changes as expected, see figure 6. Elements on the left lateral side received increased stiffness (factor eight), resulting in an ipsilateral deviation of the tongue tip during a combined activation of the GGM, GGP, TRA, and VER.
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**Figure 6: Protrusion of the tongue**

A combined activation of transversal intrinsic intrinsic tongue muscle, vertical intrinsic tongue muscle, posterior genioglossal tongue muscle, and middle genioglossal tongue muscle, with increased stiffness for elements on the left lateral cranial side, resulting in a deviation to the left hand side. Left: front view, middle: side view, right: top view

**DISCUSSION**

_Synopsis of results_

In the current study the first steps towards creation of a new tongue model are presented. The choice was made for a FE model which gives us the ability to detect causes of unexpected deformations, and enables us to adjust the inner workings of the model locally, if necessary. A FE model was created and inducing activation of different muscles and tongue movements could be visualised. Stiffness could be changed to mimic scarring effects either caused by surgery or by radiotherapy. We used Matlab to create our software to have full control over all aspects of the modelling, because standard software packages for FE modeling would have limitations regarding non-linear elastic materials.¹⁹

The deformations, as shown by the model, are comparable with descriptions of in vivo movements,²⁰ see table 1. The combined activation of the GGP, GGM, TRA, and VER is mentioned as the activation pattern for protrusion.²⁰ This behaviour is also confirmed by our model. The volume changes for the total tongue body are reasonable, although the volumes of the individual FE elements can change significantly. Therefore, implementing a volume constraint, which prevents large volume changes, but does not interfere with the movement of the tongue, is desirable. Increasing the stiffness value for several elements shows deformations as they were expected beforehand. When exact tissue parameters are known, our model should be able to mimic changes in the tissue, caused by the treatment.
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Table 1: Main actions of different tongue activations

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Description model</th>
<th>Description Agur &amp; Dalley(^{20})</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGA</td>
<td>Depression of the apex and deepening the groove</td>
<td>Depresses tongue, posterior part pulls tongue anteriorly for protrusion</td>
</tr>
<tr>
<td>GGM</td>
<td>Protrusion of the apex and depression of the dorsum</td>
<td></td>
</tr>
<tr>
<td>GGP</td>
<td>Protrusion</td>
<td></td>
</tr>
<tr>
<td>HG</td>
<td>Depression of the dorsum</td>
<td>Depresses and retracts tongue</td>
</tr>
<tr>
<td>SG</td>
<td>Retracts the tongue and lifts the dorsum</td>
<td>Retracts tongue and draws it up to create a trough for swallowing</td>
</tr>
<tr>
<td>PG</td>
<td>Elevation of the tongue</td>
<td>Elevates posterior part of the tongue</td>
</tr>
<tr>
<td>SL</td>
<td>Retraction of the tongue and elevation of the apex</td>
<td>Curls apex and sides of tongue superiorly and shortens tongue</td>
</tr>
<tr>
<td>IL</td>
<td>Retraction of the tongue and pulls tongue tip down-and backward</td>
<td>Curls tip of tongue inferiorly and shortens tongue</td>
</tr>
<tr>
<td>TRA</td>
<td>Small protrusion of the tongue and elevation of the dorsum and narrowing the tongue body</td>
<td>Narrows and elongates the tongue</td>
</tr>
<tr>
<td>VER</td>
<td>Downward movement of the tongue and slight protrusion</td>
<td>Flattens and broadens the tongue</td>
</tr>
</tbody>
</table>

Based on qualitative observations in our model and descriptions by Agur and Dalley.\(^{20}\) The genioglossal muscle is described as one muscle by Agur and Dalley, but an independent action for the posterior part is mentioned.

**PCA models**

Another group of models described in medical literature is models based on Principal Component Analysis (PCA). A PCA model describes the shape and geometry of the tongue by a small number of modes of shape deformations. An arbitrary shape of the tongue can be synthesised by a suitable combination of modes. PCA models are black-box model types. By measuring the location of five positions on the tongue, and giving those as an input to the model, the result, the 3D tongue shape is obtained with a reasonable accuracy.\(^{21,22}\) However the model predicts the shape without information about the local, internal working of the tongue.

**Choice between PCA and FE model**

A PCA model is, from a technical viewpoint, easier to develop and to control, however, the lack of information on the inner workings (black box model) is an obstacle to achieving the final goal of virtually presenting the functional results of surgery. By contrast, models based on the FE method - so called white box models - result in a 3D representation of all local actions performed on the initial shape. This modeling type has the ability to simulate the muscle fibers and branches of the hypoglossal nerve as accurately as necessary, at a cost of calculation time. This modeling type creates promising opportunities for future virtual interventions and virtual postoperative functioning.

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**Different FE models**

Two coarse FE models were developed during recent decades for the animation of tongue movements.\textsuperscript{23, 24} These models were developed to assess the function of different tongue muscles on the tongue deformation. Due to the few and relatively large elements being used, only an indication of the deformation is obtained. This makes them unsuitable for virtual surgery. A more detailed model was developed in 2005, including the jaw, velum, lips, and vocal folds, with the aim of characterising the elasticity properties of the tongue and the cheeks.\textsuperscript{25} The theoretical background of this model is comparable with our model, however this model is developed using the FE package Ansys\textsuperscript{TM}. Our model is developed in Matlab instead of a standard FE package, because in such a standard package it would not be possible to implement the muscular and neural systems, an EMG muscular innervation model and to adapt the model to virtual surgery. The three existing models are continuous models, meaning they use solid elements which are mutually connected. This manner of modeling makes it possible to retrieve a continuous course of the velocity and acceleration graphs as well. Another tongue model has developed by Dang and Honda,\textsuperscript{15} who did not use a continuous model, but made an extra division step. They also divided the tongue into solid ‘brick’ 3D quadrilateral elements as a first division step then divided each ‘brick’ into 26 cylinders connecting each node of the brick. In this way a semi-continuous model was developed. Such a model is simpler and has a shorter calculation time. However, a continuous model is easier to control and the accuracy is assumed to be higher compared to non-continuous models.\textsuperscript{26} The semi-continuous model of Dang and Honda will benefit from some advantages of a continuous model, but by implementing the extra division step, assumptions are made that are not necessary for our goal. Our research purpose was not to define a short calculation time, but to obtain high accuracy and reliable control of the model, which was achieved by using our solid 3D quadrilateral elements leading to a continuous model.

**Future steps to be taken**

The visualisation of deformations in 3D in an individualised model of the tongue, based on a FE model, makes it now possible to perform virtual tumour resections by removing and adjusting the influenced elements. By simulating surgery and the resulting functional loss an objective judgment of expected function losses will be made available. Our modeling method gives possibilities to adjust material properties in such a manner that scar and reconstructive tissue compartments can be matched. The exact location of the muscle fibers and hypoglossal nerves can be done by diffusion MRI sequences.\textsuperscript{27-30}

Further individualisation of the tongue model will be reached by implementation of EMG-signals of the various tongue muscles involved. The model should be optimised by determining muscle...
activation patterns for specific tongue movements. Next to this, the amount of FE elements should be increased to obtain a more accurate simulation and a smoother surface of the tongue. This would improve future speech synthesis too. Detailed information on tissue parameters is necessary to adequately simulate the effects of surgery. Finally a clinical evaluation is necessary to assess the accuracy of the model in a quantitative manner.

CONCLUSION

The first steps towards virtual surgery for oral cancer are taken. A coarse finite element model of the tongue is created, based on tongue shapes segmented from a MRI scan. Tongue movements are simulated based on single or combined muscle contractions. As the internal workings of the model are adjustable, changes in anatomy or tissue properties can be simulated, mimicking scar tissue, surgical reconstruction or radiotherapy effects. Further development of the model can make virtual surgery possible for assessment and visualisation of the postoperative functional results, to reach the final goal to optimise personalised medicine of oral cancer.
REFERENCES


