Advanced Visual Medicine

Simulation & Visualization for Therapy Planning

Stefan Zachow
Department of Visualization & Data Analysis
Medical Planning Group
Zuse Institute Berlin (ZIB) - Germany

Computer Assisted Medicine

Due to rapidly evolving medical imaging techniques *Visualization in Medicine* becomes more and more important

Besides mere *visualization* of medical data, there is an increasing demand for performing *modifications* or even *functional simulations* based on individual data for extended diagnosis and *therapy planning*

http://www.zib.de/visual/medical/projects

Computer Assisted Medicine

VIS08 VIS • INFOVIS • VAST

Goals

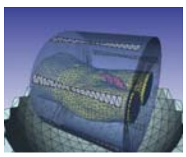
- **quantitative, patient specific** medicine
- **individual** therapy or surgery planning

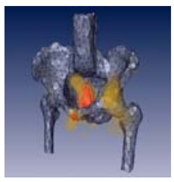
Computer Assisted Medicine

VIS08 VIS • INFOVIS • VAST

3D-Geometry Reconstruction

Medical Image Data → Virtual Patient → Simulation / Treatment Plan → Clinical Implementation





Outline

Generation of virtual 3D anatomy

- Geometric reconstruction from medical image data and visualization, e.g. with amira®
- Statistical 3D shape models, i.e. anatomy including its variation

3D model based therapy planning

- Interactive modification (structure, properties, etc.)
- Numerical simulation (deformation, flow, pressure, etc.)

Virtual 3D Anatomy

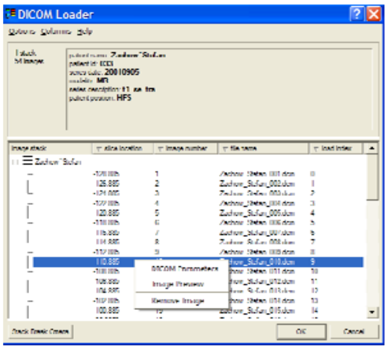
Requirements

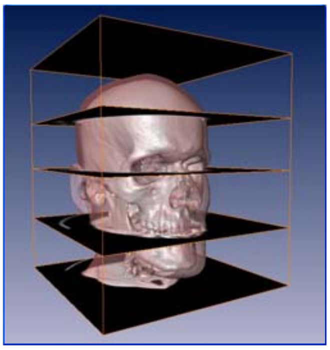
- **Morphology**
  boundaries of, and interfaces between anatomic structures of interest
- **Geometry**
  consistent, high quality surface meshes and volumetric grids (for planning and simulation)
- **Atlases**
  mean or representative shapes of anatomic structures including shape variation

Virtual 3D Anatomy

Vis08 VIS • INFOVIS • VAST

From medical image data (CT, MRI, ...)





amira ®

Virtual 3D Anatomy

Vis08 VIS • INFOVIS • VAST

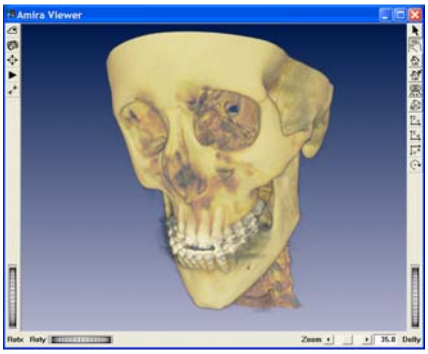
Consecutive slices of medical 2D images are converted into a 3D scalar field

- Scalars depend on the imaging modality, thus having a tissue related meaning
- Scalars can be visualized directly via volume rendering techniques using an appropriate mapping to display colors
- Scalars can be mapped to labels (single, multiple), which is called tissue classification or segmentation
- Boundaries of labeled regions can be computed and visualized using surface rendering techniques

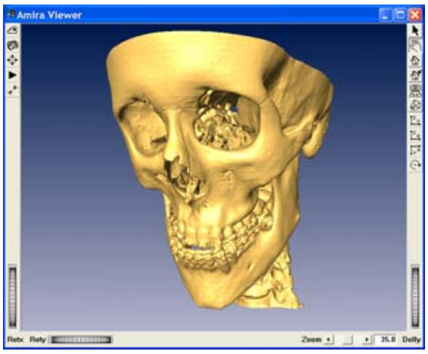
Virtual 3D Anatomy

Vis08 VIS • INFOVIS • VAST

Visualization (Diagnostics)



Volume Rendering



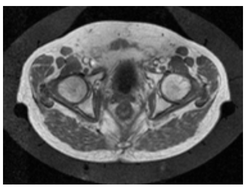
Iso-Surface (bone threshold)

Virtual 3D Anatomy

Vis08 VIS • INFOVIS • VAST

Medical Image Segmentation

- Image decomposition into contiguous semantic regions, e.g. homogeneous tissue compartments



Virtual 3D Anatomy

Segmentation of medical image data typically is a labor intensive process, highly depending on

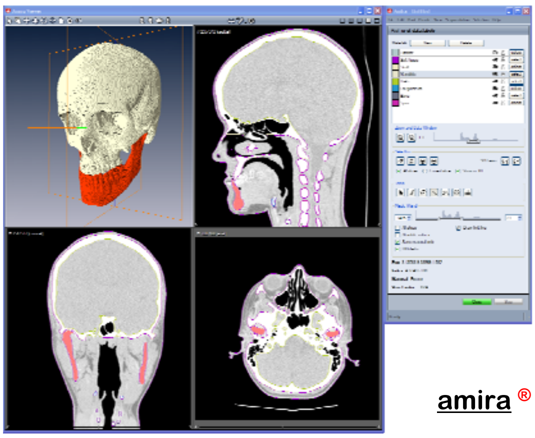
- image quality (specificity, signal to noise ratio)
- image resolution (voxel size, number of slices)
- number of anatomic structures
- homogeneity of tissue structures
- separability of adjacent structures

Appropriate software tools are needed!

Virtual 3D Anatomy

Tissue Classification / Segmentation

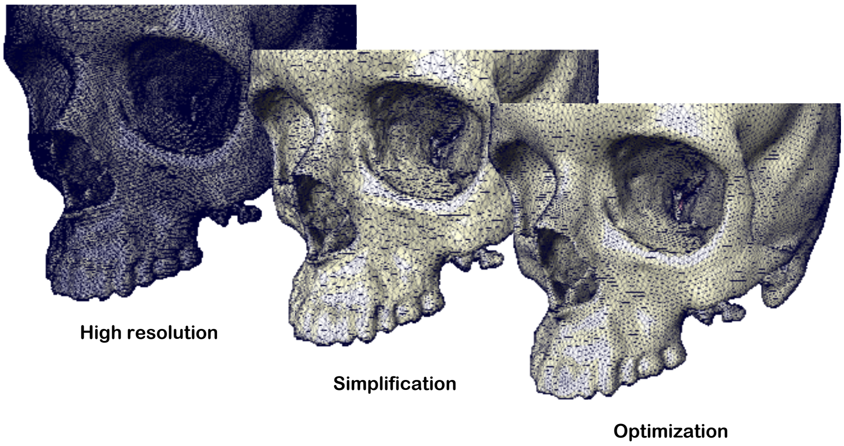
- thresholding
- 2D/3D region growing
- lasso, brush, snakes
- intelligent scissors
- inter- / extrapolation
- morphological operators
- smoothing, denoising
- … to be improved !



amira ®

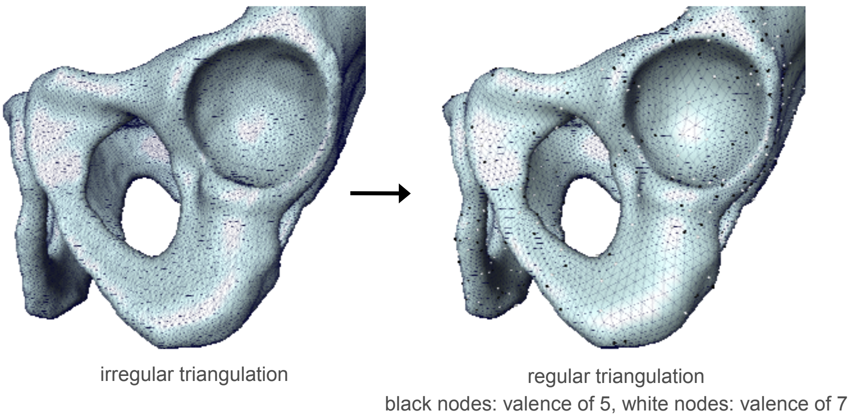
Virtual 3D Anatomy

Tissue Boundaries / Surface Meshes



Virtual 3D Anatomy

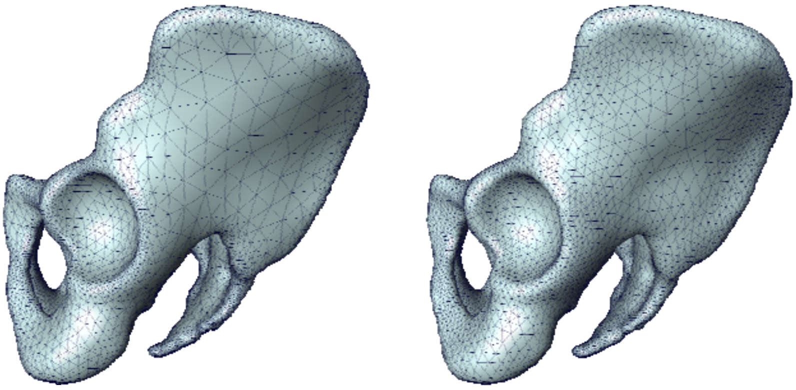
Explicit remeshing with constraints



Zilske M, H Lamecker, S Zachow: Remeshing of non-manifold surfaces. Eurographics (2008)

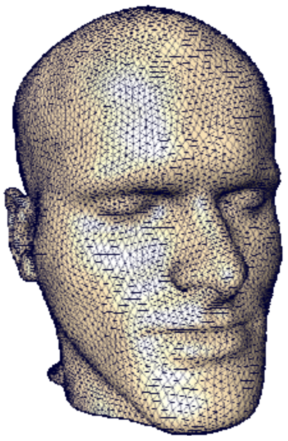
Virtual 3D Anatomy

Node density control (volumetric constraints)



IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 15/76

Virtual 3D Anatomy



Zachow S, Zilske M, Hege HC: 3D Reconstruction of Individual Anatomy from Medical Image Data: Segmentation and Geometry Processing. 25th ANSYS Conference & CADFEM Users' Meeting, Dresden, ZIB Report 07-01 (2007)

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 16/76

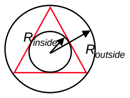
Virtual 3D Anatomy

Digital Anatomy

Surface meshes and volumetric grids for finite element analysis

- multi-material
- unstructured
- locally adaptive resolution
- controlled element quality

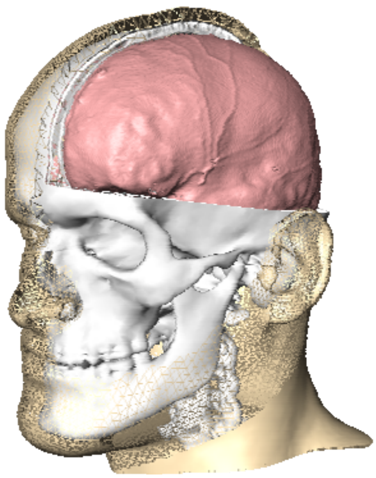
$$Quality = \frac{R_{inside}/R_{outside}}{(R_{inside}/R_{outside})_{ideal}}$$



Virtual 3D Anatomy

Virtual Patient Models

- contain all relevant anatomic structures
- are a faithful and consistent reproduction of real anatomy
- can be further processed with software tools
- are the foundation for computer assisted therapy planning



Virtual 3D Anatomy

Statistical Shape Models

- do represent not only a single shape of an anatomical structure but also its *shape variation* with regard to a set of similar structures
- are an extension of static reference anatomy (so called anatomical atlases)

… the "new anatomy" !

http://www.zib.de/lamecker/publications

Statistical 3D Shape Models

Principal Component Analysis

1. Compute the mean shape

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \;\in \mathbb{R}^{3m}$$

2. Compute deviations from the mean shape

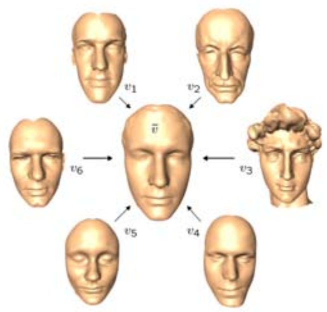
$$D = ((v_1 - \bar{v}), \ldots, (v_d - \bar{v})) \;\in \mathbb{R}^{3m \times n}$$

3. Compute the covariance matrix

$$C = \frac{1}{n} D D^T \;\in \mathbb{R}^{3m \times 3m}$$

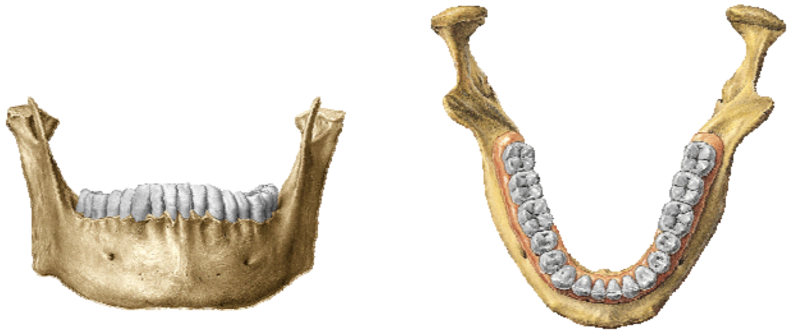
4. Compute eigenvalues and -vectors of C

$$C p_k = \lambda_k p_k$$



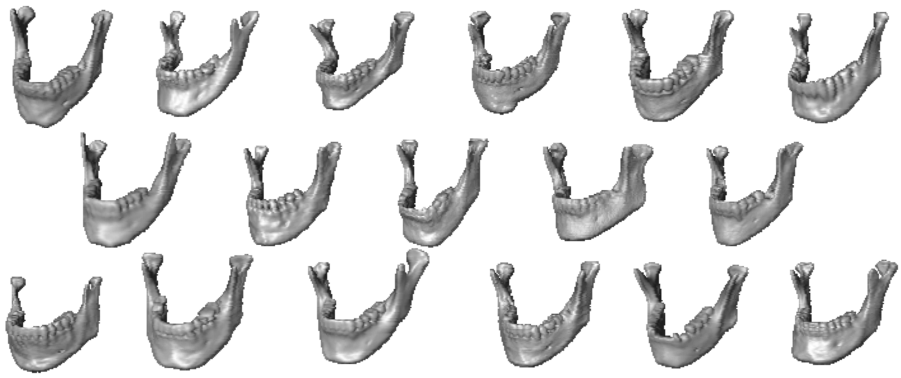
$$S(\mathbf{b}, T) = T\left(\bar{\mathbf{v}} + \sum_{k=1}^{n} b_k \mathbf{p}_k\right)$$

Example: Mandible



Härle et al.: *Atlas of Craniofacial Osteosynthesis*. Thieme (1999)

Mandibular Shapes are Manifold

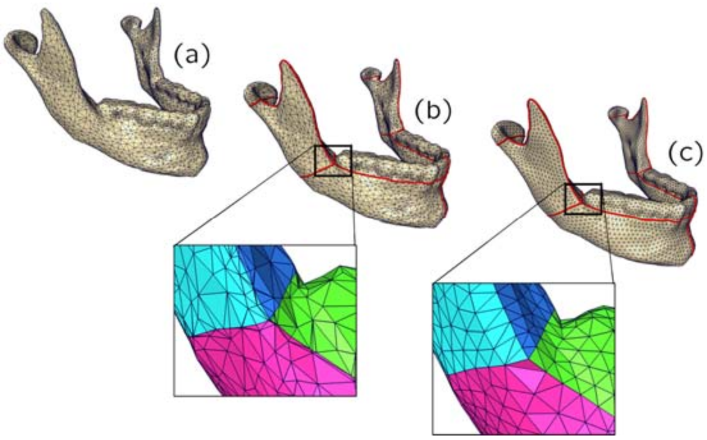


Statistical 3D Shape Models

Consistent Shape Decomposition

Statistical 3D Shape Models

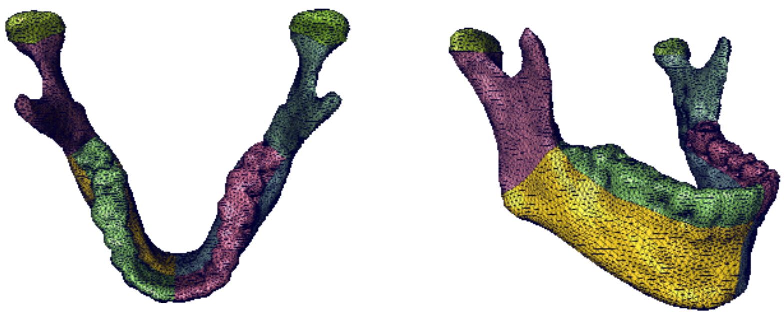
Explicit Remeshing with Constraints



Statistical 3D Shape Models

VIS08 VIS • INFOVIS • VAST

Reference Triangulation

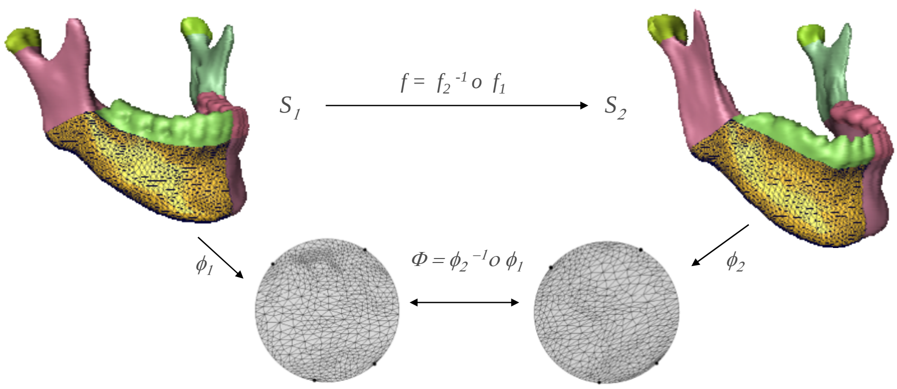


IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 25/76

Statistical 3D Shape Models

VIS08 VIS • INFOVIS • VAST

Shape Matching - Surface Parameterization and Correspondence Mapping



IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 26/76

Statistical 3D Shape Models

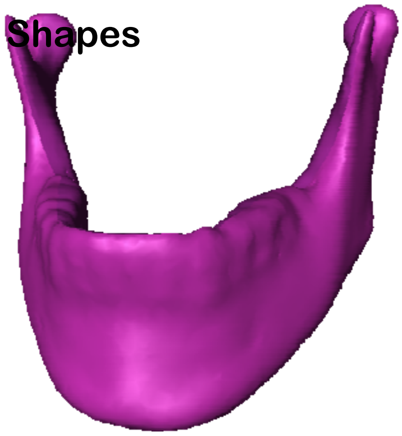
- correspondence maps → shape space $\mathbf{v}_k \in \mathbb{R}^{3m}$
  m = number of surface nodes
  k = 1,...,n with n = number of shapes
- principal component analysis on vectors $\mathbf{p}_k \in \mathbb{R}^{3m}$
  average shape
  eigenvectors of covariance matrix (modes of variation)
- statistical shape model $\mathcal{S}(\mathbf{b}, T) = T\left(\bar{\mathbf{v}} + \sum_{k=1}^{n} b_k \mathbf{p}_k\right)$
- essential degrees of freedom $n' \ll n$
  rigid-body / affine transformation T
  weights of modes of variation $b_k \in \mathbb{R}$

Statistical 3D Shape Models

Averaging 3D Shape

Statistical 3D Shape Models

Averaging 3D Shapes

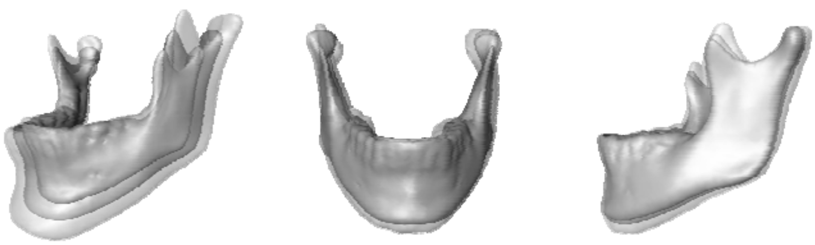


$$S(\mathbf{b}, T) = T(\bar{v} + \sum_k b_k \mathbf{p}_k)$$

Statistical 3D Shape Models

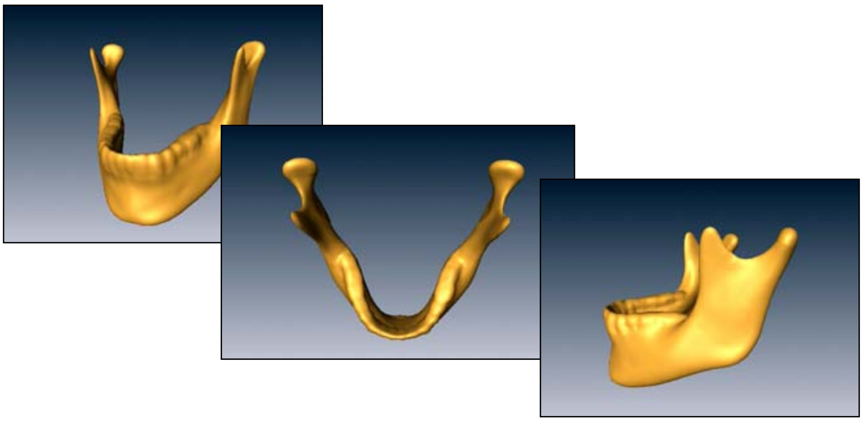
Characteristic Shape Variations

- the principal modes of variation are sorted according to their eigenvalues



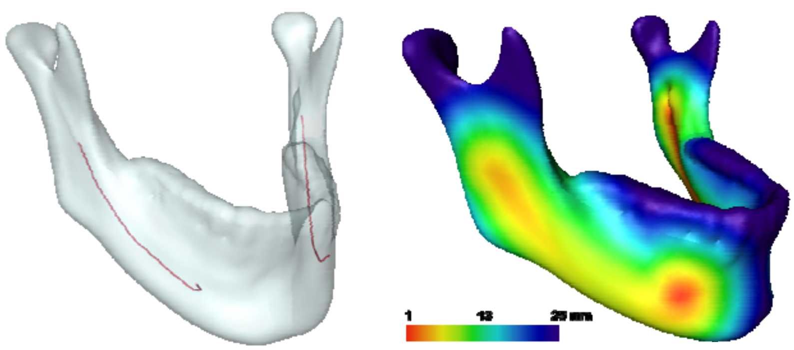
1^{st} mode 2^{nd} mode 3^{rd} mode

Characteristic Shape Variations



Animation: Principal modes of variation are sorted according to their eigenvalues

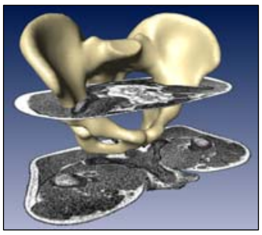
Mandibular nerve is added to the statistical shape model

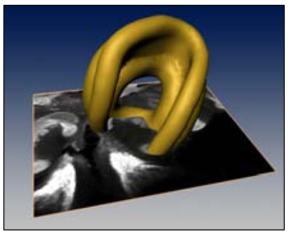


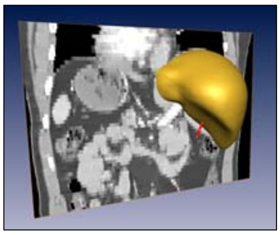
Zachow S, H Lamecker, B Elsholtz, M Stiller: Is the course of the mandibular nerve deducible from the shape of the mandible? Int. J. of Computer Assisted Radiology and Surgery, Springer, pp. 415-417 (2006)

Model-based 3D Segmentation

Segmentation of medical image data using statistical 3D shape models







Model-based 3D Segmentation

Utilization of a-priori knowledge of the shape of the structure that is to be segmented

- Compilation of a set of 3D shapes from sufficient representative samples
- Generation of a statistical 3D shape model
- Adaptation of the 3D shape model to image data of the respective structure

Model-based 3D Segmentation

R is an unknown shape that is to be reconstructed from image data

Solve optimization problem

$$(\mathbf{b}^*, T^*) = \underset{\mathbf{b},T}{\operatorname{argmin}} \|R - S(\mathbf{b}, T)\|^2$$

Since R is unknown, solve iteratively

$$R^i = S(\mathbf{b}^i, T^i) = \text{segmentation at "time" } i$$

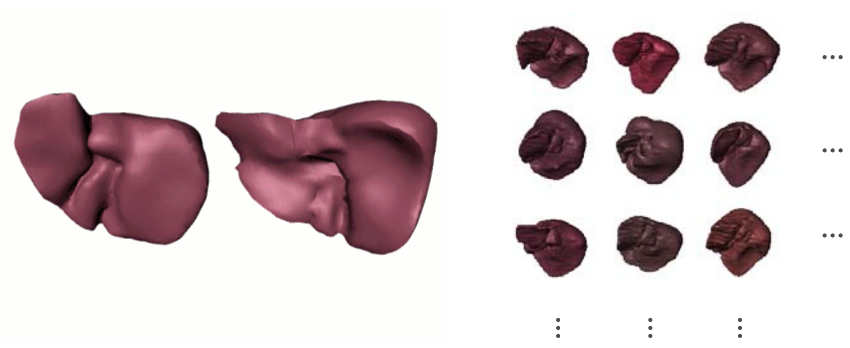
$$\Delta R^i = \text{deformation vector field}$$

$$(\mathbf{b}^{i+1}, T^{i+1}) = \underset{\mathbf{b},T}{\operatorname{argmin}} \|(R^i + \Delta R^i) - S(\mathbf{b}, T)\|^2$$

Displacements ΔR encode specific image characteristics

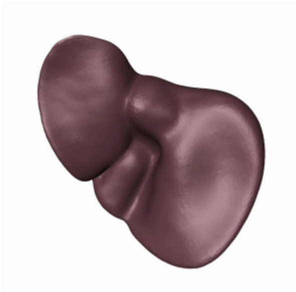
Model-based 3D Segmentation

Example: Liver from contrast enhanced CT

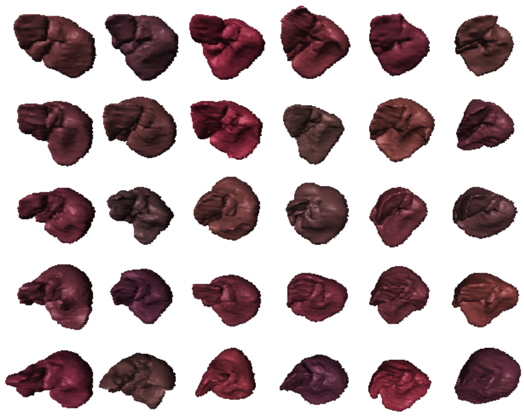


Model-based 3D Segmentation

Averaged liver (150++ individual liver shapes)



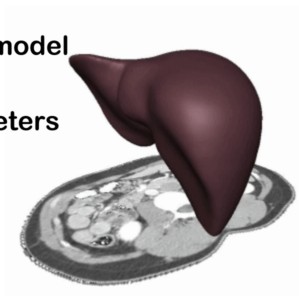
1st mode of variation



Model-based 3D Segmentation

Automatic segmentation of the liver from contrast enhanced CT-data

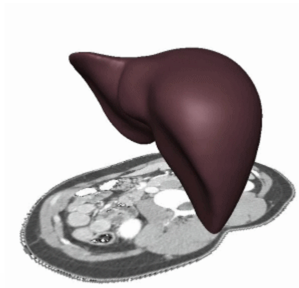
- Automatic initial positioning of the shape model according to anatomical landmarks
- Automatic initialization of intensity parameters via histogram analysis
- Adaptation of the statistical shape model (weighted combination of eigenmodes) to image features
- Shape constrained free form deformation



D. Kainmüller, Th. Lange, H. Lamecker: *Shape constrained automatic segmentation of the liver based on a heuristic intensity model.* MICCAI Workshop on 3D Segmentation in the Clinic: A Grand Challenge, 2007

Model-based 3D Segmentation

Automatic segmentation of the liver from contrast enhanced CT data

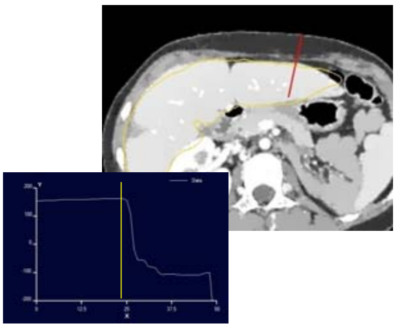


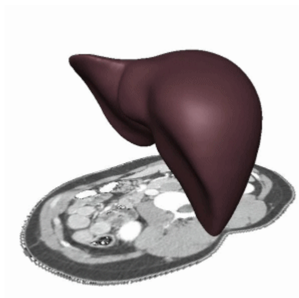
$$\min_{b_k,T} \left\| (\mathbf{v}+\Delta\mathbf{v}) - T\left(\bar{\mathbf{v}} + \sum_{k=1} b_k \mathbf{p}_k\right)\right\|^2$$

D. Kainmüller, Th. Lange, H. Lamecker: *Shape constrained automatic segmentation of the liver based on a heuristic intensity model.* MICCAI Workshop on 3D Segmentation in the Clinic: A Grand Challenge, 2007

Model-based 3D Segmentation

Automatic segmentation of the liver from contrast enhanced CT data





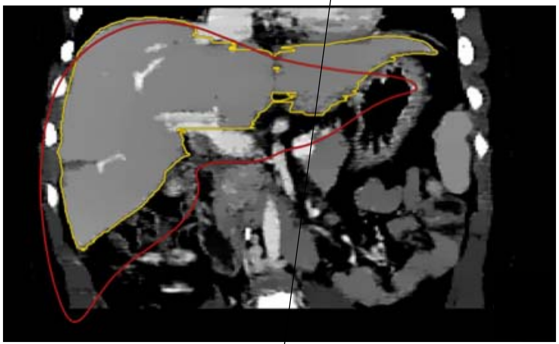
D. Kainmüller, Th. Lange, H. Lamecker: *Shape constrained automatic segmentation of the liver based on a heuristic intensity model.* MICCAI Workshop on 3D Segmentation in the Clinic: A Grand Challenge, 2007

Model-based 3D Segmentation

Automatic segmentation of the liver from contrast enhanced CT data

yellow
: **manual reference segmentation**

red
: **adaptation of the 3D shape model**



D. Kainmüller, Th. Lange, H. Lamecker: *Shape constrained automatic segmentation of the liver based on a heuristic intensity model.* MICCAI Workshop on 3D Segmentation in the Clinic: A Grand Challenge, 2007

Model-based 3D Segmentation

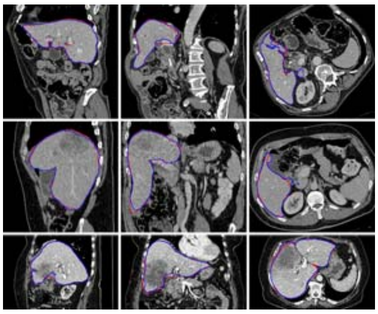
MICCAI 2007 – 3D Segmentation in the Clinic

Segmentation of 10 data sets (liver tissue + tumors) in < 3h

Scoring 100 = reference segmentation by radiologist
75 = same error as another manual reference segmentation

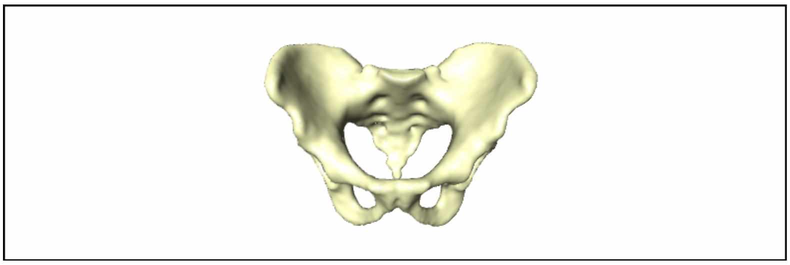
Combination of different volumetric overlap and surface distance measures

1	ZIB / Charité	68
2	GE Hungary ZRT	57
3	Definiens AG	53
4	KU Leuven I	51
5	Siemens Research	51
6	KU Leuven II	42
7	University Tokyo	42
8	University Chicago	6



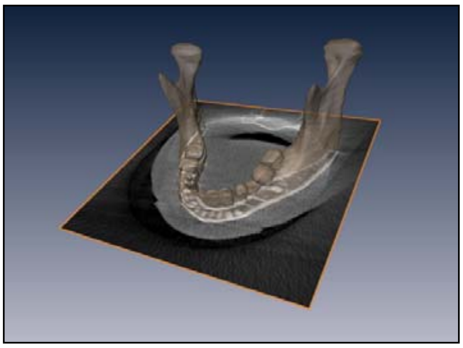
Model-based 3D Segmentation

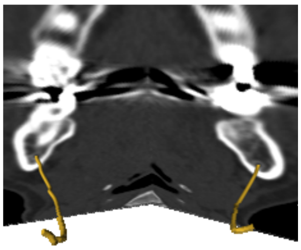
Example: Pelvic bones from CT or MRI data



Model-based 3D Segmentation

Example: Mandible from Cone Beam CT (DVT) including mandibular nerve

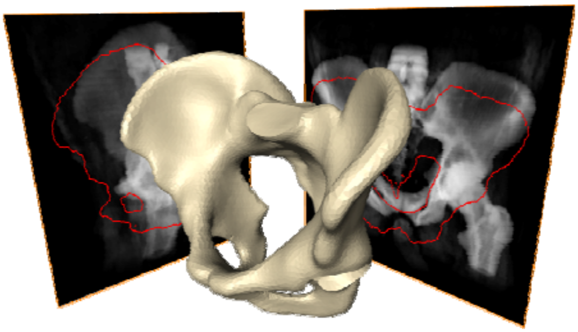




Lamecker H, S Zachow, A Wittmers et al.: Automatic Segmentation of Mandibles in Low-Dose CT-Data. Int. J. of Computer Assisted Radiology and Surgery, Springer, pp. 393-395 (2006)

Model-based 3D Segmentation

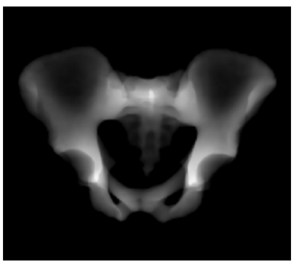
Example: Pelvic bones from 2D X-ray images



IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 45/76

Model-based 3D Segmentation

Segmentation of pelvic bones from X-ray images



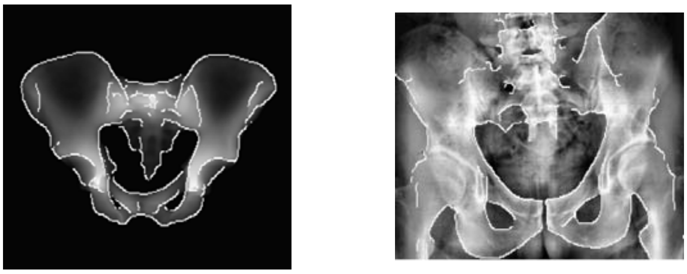
Left: GPU computation of thickness image according to the beam propagation length through the shape model

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 46/76

Model-based 3D Segmentation

Vis08 VIS • INFOVIS • VAST

Segmentation of pelvic bones from X-ray images



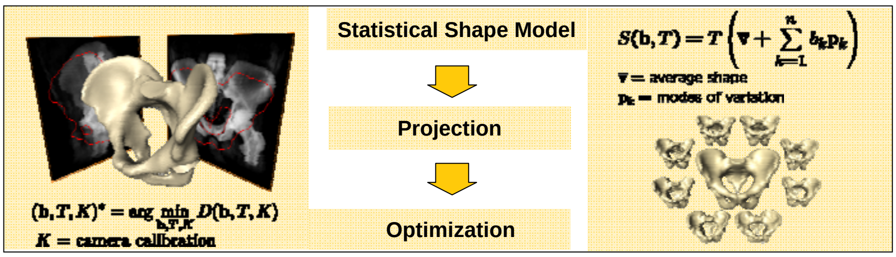
Canny edge detection in projection and X-ray images

Model-based 3D Segmentation

Vis08 VIS • INFOVIS • VAST

D = ‚distance' between projected model and X-ray

K = camera calibration



$$D = \int_{\mathbf{x}\in s} d(\mathbf{x}, s')^2 dx + \int_{\mathbf{x}\in s'} d(\mathbf{x}, s)^2 dx.$$

$$d(\mathbf{x}, s') = \min_{\mathbf{y}\in s'} \|\mathbf{x} - \mathbf{y}\|$$

Model-based 3D Segmentation

VIS08 VIS • INFOVIS • VAST

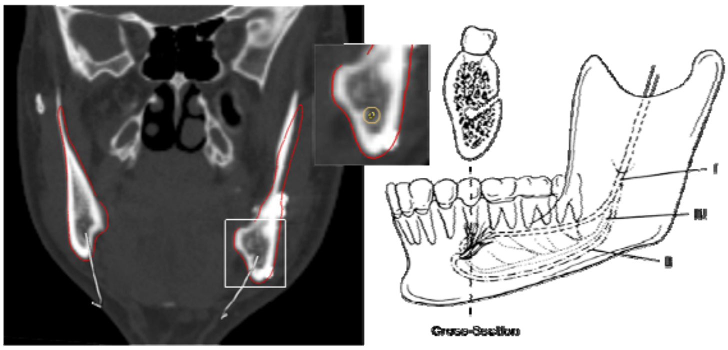
Example: Mandibles including nerve from panoramic X-ray images (OPG)

IEEE Visualization 2008 — Stefan Zachow: Simulation & Visualization for Surgical Planning — 49/76

Model-based 3D Segmentation

VIS08 VIS • INFOVIS • VAST

Segmentation of mandibles including nerve from panoramic X-ray images (OPG)

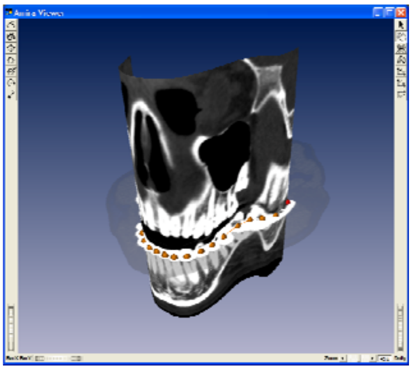


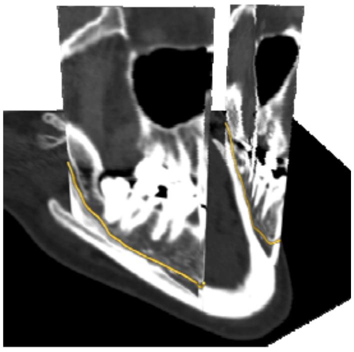
IEEE Visualization 2008 — Stefan Zachow: Simulation & Visualization for Surgical Planning — 50/76

Model-based 3D Segmentation

Vis08 VIS • INFOVIS • VAST

Segmentation of mandibles including nerve from panoramic X-ray images (OPG)





Therapy Planning

Vis08 VIS • INFOVIS • VAST

Part II

3D Model-based Therapy Planning

Therapy Planning

VIS08 VIS • INFOVIS • VAST

Mental and technical preparation of complex medical interventions

- **Assessment**
  Type, location and extent of pathologies, functional (and esthetic) impairments, etc.
- **Strategy**
  Tools and methods, access paths, security margins, protection of vulnerable structures, etc.
- **Insight**
  Pre-interventional assessment of general outcome, effects on physiology, biomechanics, etc.

Therapy Planning

VIS08 VIS • INFOVIS • VAST

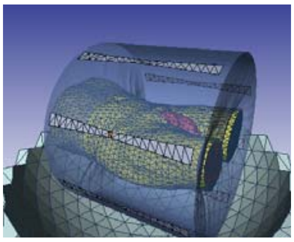
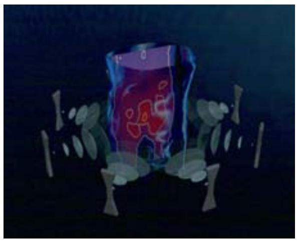
- Oncology - Regional Hyperthermia
- Maxillofacial Surgery - Osteotomy / Bone Relocation
- Craniofacial & Neurosurgery - Craniosynostosis
- Plastic and Reconstructive Surgery
- Ear, Nose and Throat Surgery - Rhinosurgery
- Orthopedic Surgery - Implants, Biomechanics
- ...

www.zib.de/visual/projects

Therapy Planning in Oncology

Regional Hyperthermia

- Heating up tumor tissue above 42°C using radio waves without damaging surrounding tissue

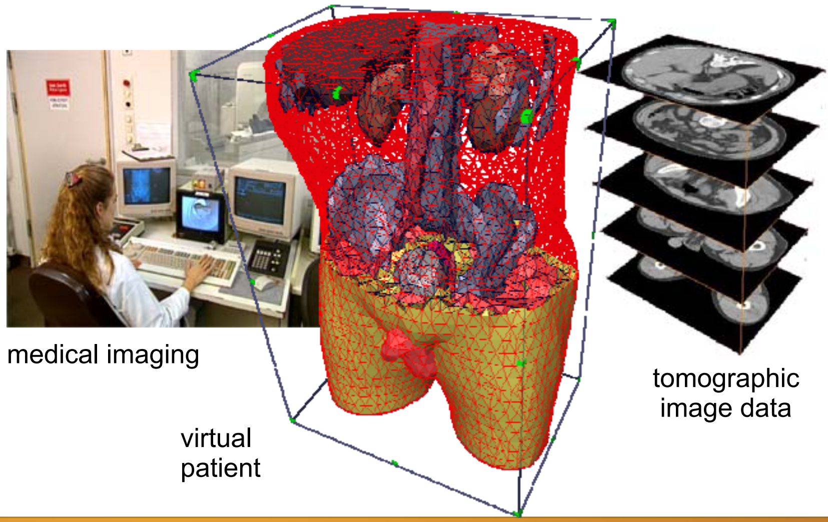
www.zib.de/visual/projects/hyperthermia

Therapy Planning in Oncology

Regional Hyperthermia

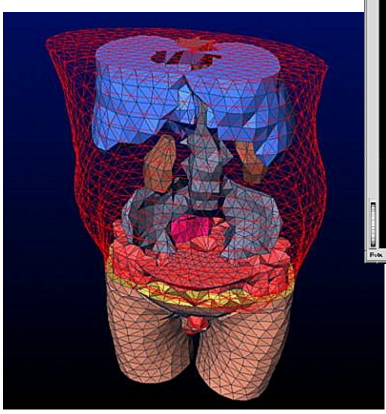
- An individual anatomic model of a tumor patient is generated
- The electro-magnetic field has to be computed according to the parameters of the applicator
- Energy distribution has to be computed within the patient model on basis of a heat transport equation as well as the specific absorption rates of tissues
- Applicator parameters, i.e. amplitudes and phases of the signals being sent to the antennas, are optimized in order to focus the heat within the tumor

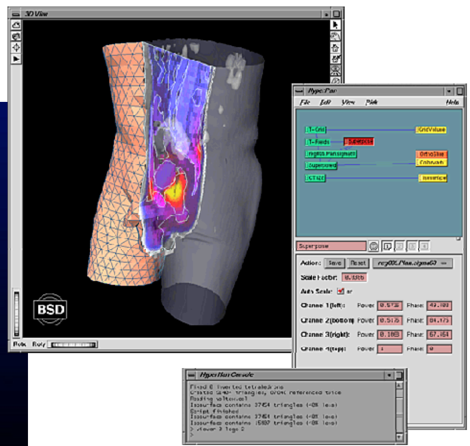
Therapy Planning in Oncology



Therapy Planning in Oncology

Planning: E-field simulation

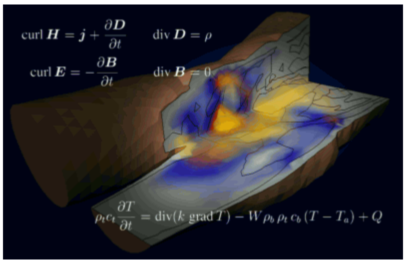




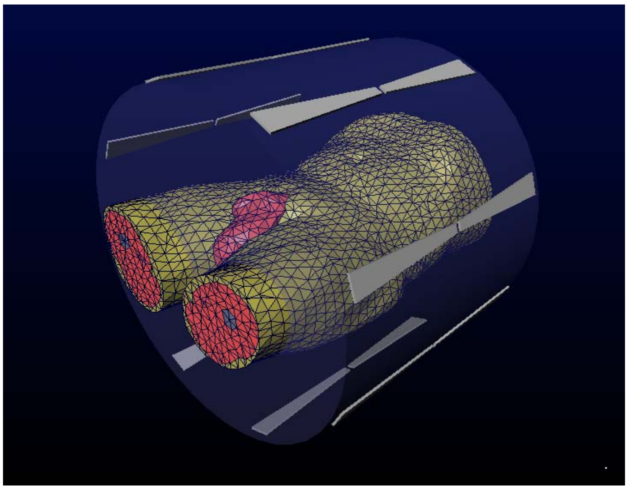
Therapy Planning in Oncology

Regional Hyperthermia

- Field calculation: Maxwell‘s equations
- Temperature distribution: Heat transport equation



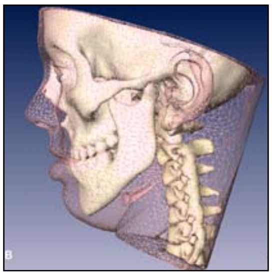
Therapy Planning in Oncology

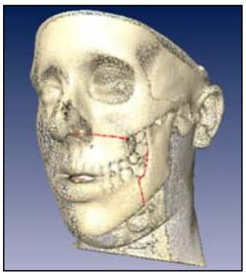


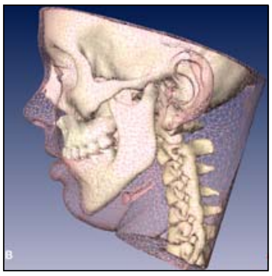
Therapy Planning in Maxillofacial Surgery

Maxillofacial Surgery

Bone cuts, bone relocations, and soft tissue prediction







www.zib.de/visual/projects/cas

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 61/76

Therapy Planning in Orthognathic Surgery

Dysgnathia

congenital pathologic development of the maxilla and/or mandible

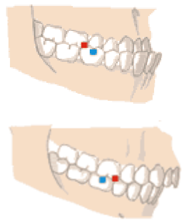
Patients of Prof. H.-F. Zeilhofer (Basel, Switzerland)

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 62/76

Therapy Planning in Orthognathic Surgery

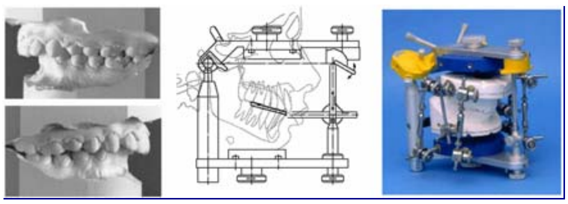
Relocation of the Jaws

- Bone cuts (osteotomies) and
- Bone relocations to achieve dental occlusion & facial harmony

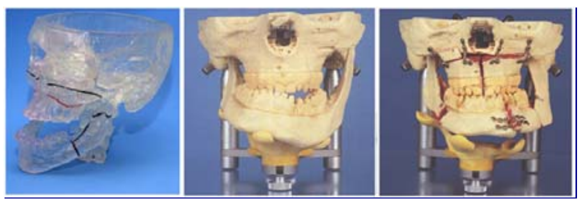


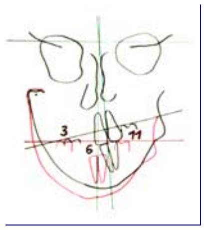
Härle et al: *Atlas of Craniomaxillofacial Osteosynthesis*. Thieme (1999)

Therapy Planning in Orthognathic Surgery



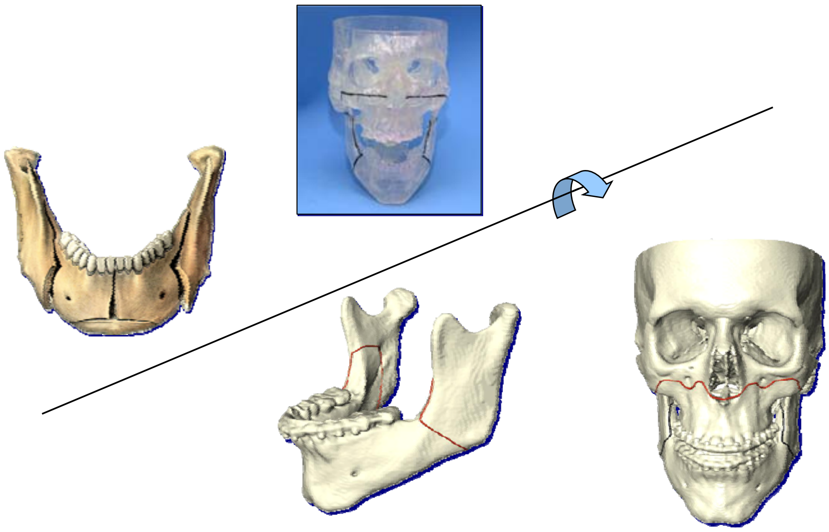
SAM Präzisionstechnik GmbH





Fuhrmann et al: Journal of Orofac. Orthop. (1996)

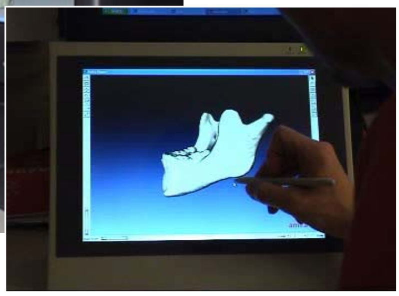
Therapy Planning in Orthognathic Surgery



Therapy Planning in Orthognathic Surgery

Video: Patient of Dr. A. Westermark (Stockholm, Sweden)

Therapy Planning in Orthognathic Surgery



Computer-assisted osteotomy planning

Therapy Planning in Maxillofacial Surgery

Soft Tissue Prediction

- based on the theory of 3D elasticity
- using a biomechanical tissue model
(in the simplest case homogeneous and isotropic with Young's modulus E and Poisson ratio ν)

Stress-strain relationship

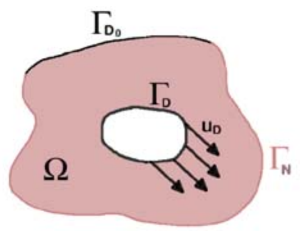
$$\sigma_{ij} \approx \frac{E}{1+\nu}\left(\varepsilon_{ij} + \frac{\nu}{1-2\nu}\varepsilon_{ll}\delta_{ij}\right)$$

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right) + \ldots$$

Minimization of internal deformation energy

$$W(\mathbf{u}) := \frac{1}{2}\int_{\Omega} \varepsilon : \sigma \, dV \longrightarrow min$$

Numerical solution of the Lamé-Navier equation



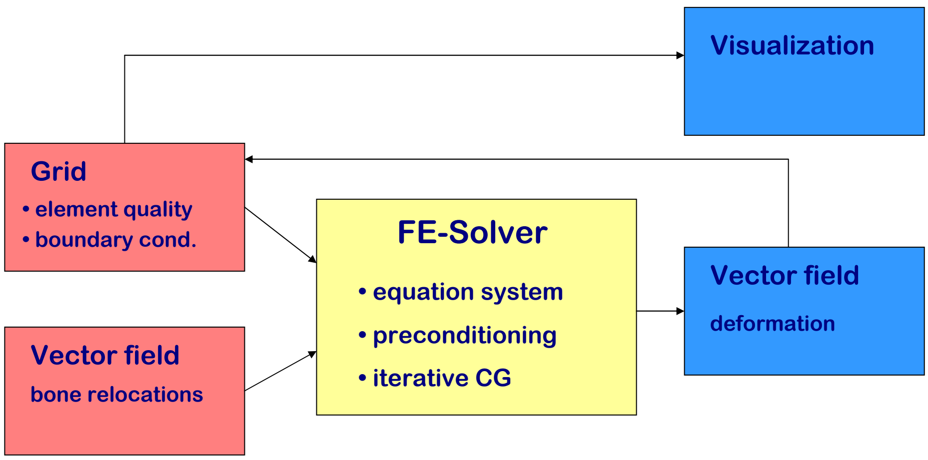
$$\frac{E}{2(1+\nu)}\left(\frac{1}{1-2\nu}\nabla(\nabla\cdot u(\mathbf{x})) + \Delta u(\mathbf{x})\right) = 0 \quad in\ \Omega$$

$$u(\mathbf{x}) = u_{D_0}(\mathbf{x}), \quad \mathbf{x} \in \Gamma_{D_0} \subset \partial\Omega$$

$$u(\mathbf{x}) = u_D(\mathbf{x}), \quad \mathbf{x} \in \Gamma_D \subset \partial\Omega$$

$$\sigma(\mathbf{x}) \cdot \mathbf{n} = 0, \quad \mathbf{x} \in \Gamma_N \subset \partial\Omega$$

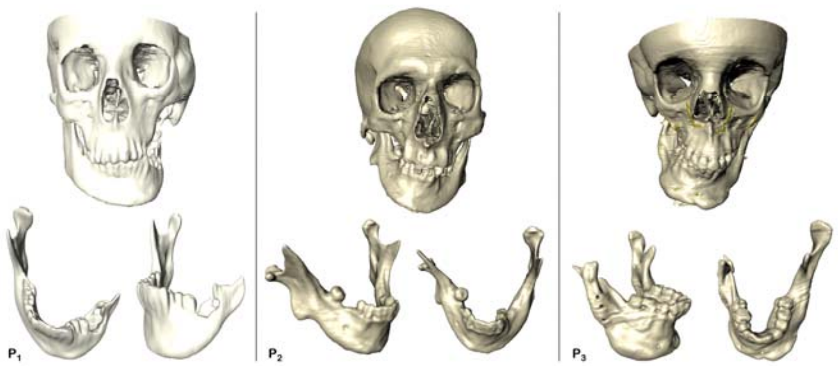
Osteotomy Planning with Soft Tissue Prediction



Therapy Planning in Maxillofacial Surgery

Vis08 VIS • INFOVIS • VAST

Severe Mandibular Dysplasia



www.zib.de/visual/projects/mandiblerecon

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 71/76

Therapy Planning in Maxillofacial Surgery

Vis08 VIS • INFOVIS • VAST

Severe Mandibular Dysplasia

- due to tumor related bone resections or craniofacial microsomia
- Reconstruction cannot be guided by the symmetry of anatomical structures
- Either autologous bone grafts or implants are used for reconstruction
- A statistical shape model of a normally developed mandible is used as a reconstruction template
- Adaptation to unaffected structures

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 72/76

Partial Reconstruction of Bone Structures

Zachow S, H Lamecker B Elsholtz, M Stiller: Reconstruction of mandibular dysplasia using a statistical 3D shape model. Proc. Computer Assisted Radiology and Surgery (CARS), pp. 1238-1243 (2005)

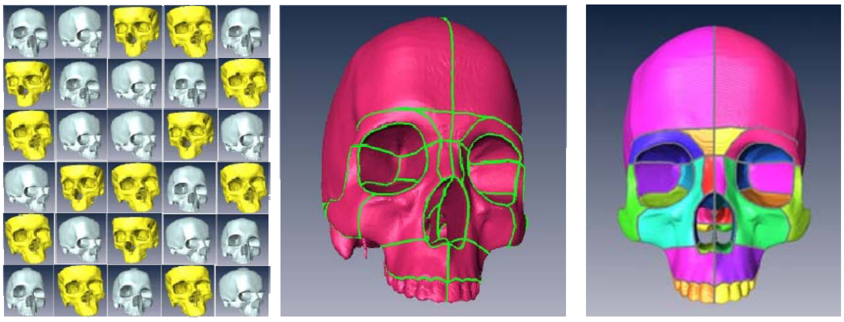
Reconstruction Proposal (adapted shape model)

$$d_{\mathrm{rms}}(\mathcal{S}(\mathbf{b},T),\mathcal{S}') = \sqrt{\frac{1}{|\mathcal{S}|+|\mathcal{S}'|}\left(\int_{\mathbf{x}\in\mathcal{S}} d(\mathbf{x},\mathcal{S}')^2 d\mathcal{S} + \int_{\mathbf{x}\in\mathcal{S}'} d(\mathbf{x},\mathcal{S})^2 d\mathcal{S}\right)}.$$

Therapy Planning in Maxillofacial Surgery

Vis08 VIS • INFOVIS • VAST

A statistical 3D shape model of the skull



Together with A. Schramm (BWK Ulm), E. Barth, K. Kubiack (MH Hannover)

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 75/76

Therapy Planning in Cranio-Neurosurgery

Vis08 VIS • INFOVIS • VAST

Surgical Correction of Skull Deformities

- Prematurely ossified cranial sutures in infants lead to skull deformities within the growth process
- Surgical correction is necessary to prevent functional impairment of the brain and to improve a patient’s appearance
- A preoperative planning method of reshaping the cranium with the help of a statistical shape model has been developed

www.zib.de/visual/projects/craniosynos

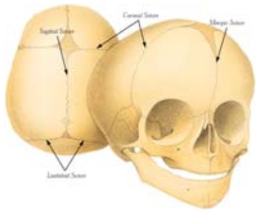
IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 76/76

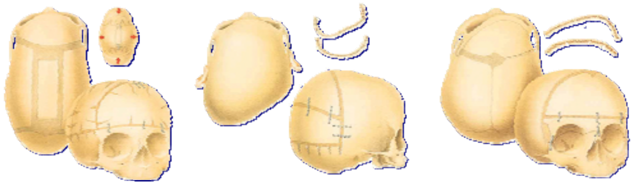
Therapy Planning in Cranio-Neurosurgery

Surgical Correction of Skull Deformities

Craniosynostosis

pathologic development of the neurocranium

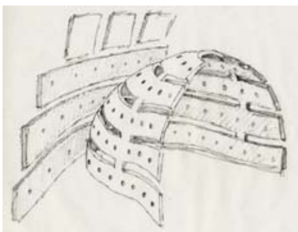


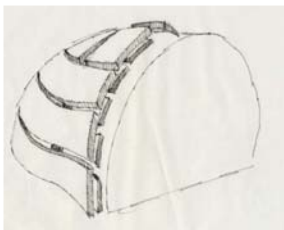


Therapy Planning in Cranio-Neurosurgery

Surgical Correction of Skull Deformities

- Fragmentation, reshaping and reorganisation of cranial bone structures
- No target specification - aesthetic result is difficult to predict



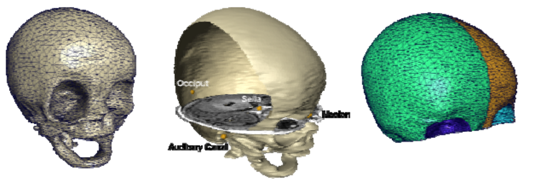


H. Haberl, 2002

Therapy Planning in Cranio-Neurosurgery

Vis08 VIS • INFOVIS • VAST

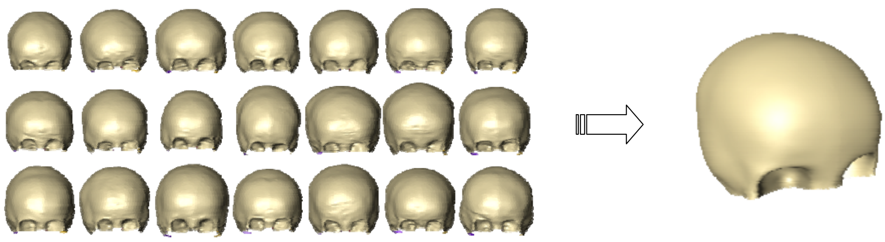
A Statistical Shape Model of the Skull



MRI data of 21 patients

age: 3 to 10 months

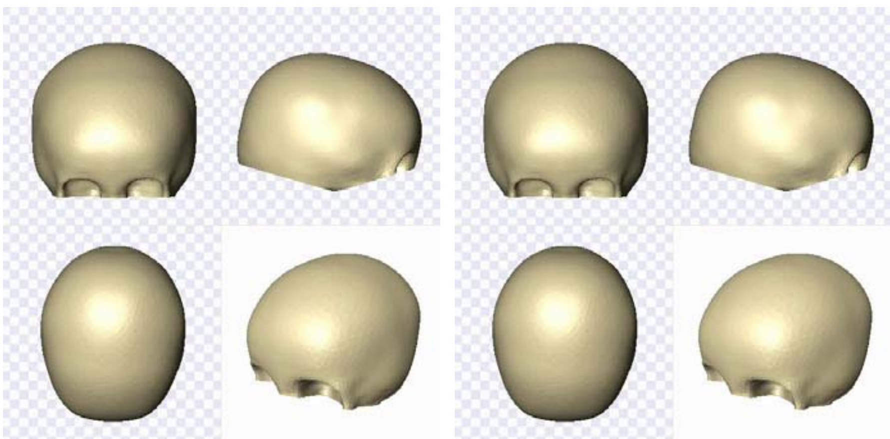
male/female



IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 79/76

Therapy Planning in Cranio-Neurosurgery

Vis08 VIS • INFOVIS • VAST

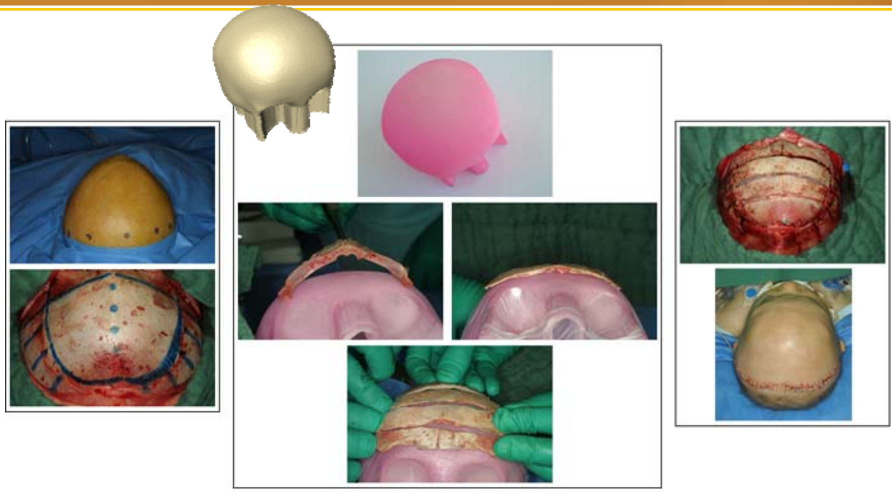


Animation: 1st and 2nd mode of principal variation

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 80/76

Therapy Planning in Cranio-Neurosurgery

Vis08 VIS • INFOVIS • VAST



Lamecker H, S Zachow, Hege HC, Zöckler M, Haber, H: Surgical Treatment of Craniosynostosis based on a Statistical 3D-Shape Model - First Clinical Application. Int. J. of Computer Assisted Radiology and Surgery, Springer, pp. 253-255 (2006)

Therapy Planning in Orbit-Surgery

Vis08 VIS • INFOVIS • VAST

Orbital Wall Fractures

enophthalmus

orbital floor reconstruction

postoperative result

blow out fracture

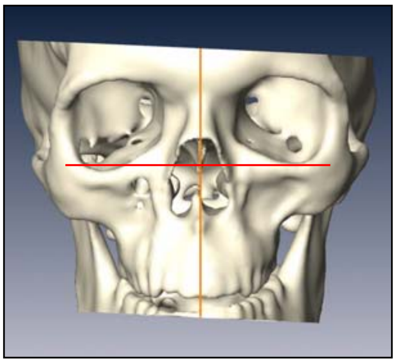
postoperative assessment

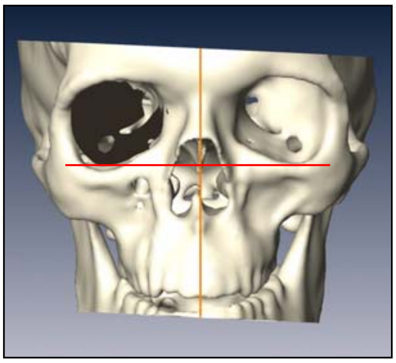
www.zib.de/visual/projects/orbita

Therapy Planning in Orbit-Surgery

Vis08 VIS • INFOVIS • VAST

Mirroring of the Bony Orbit





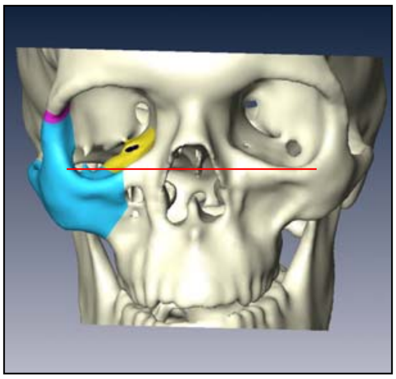
Cooperation with A. Schramm (BWK Ulm), E. Barth (MH Hannover), R Kontio (Helsinki)

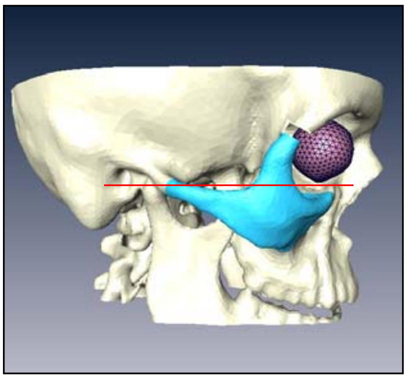
IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 83/76

Therapy Planning in Orbit-Surgery

Vis08 VIS • INFOVIS • VAST

Elevation of the Zygomatic Bone





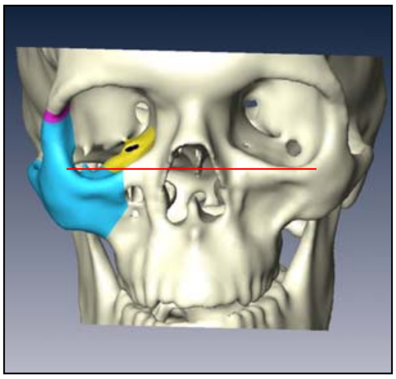
Planning in Cooperation with Dr. Kontio, Helsinki

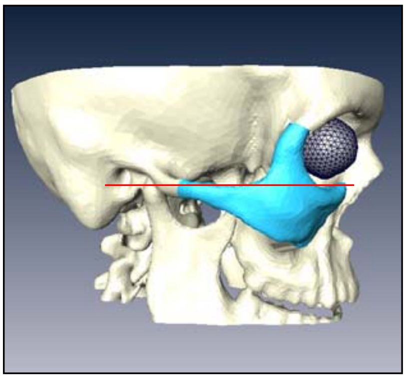
IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 84/76

Therapy Planning in Orbit-Surgery

Vis08 VIS • INFOVIS • VAST

Elevation of the Zygomatic Bone





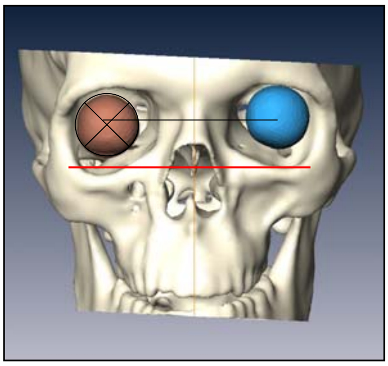
Planning in Cooperation with Dr. Kontio, Helsinki

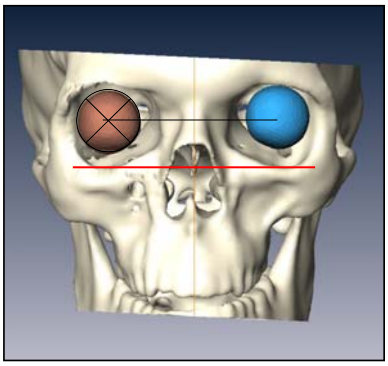
IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 85/76

Therapy Planning in Orbit-Surgery

Vis08 VIS • INFOVIS • VAST

Elevation of the Eye Ball

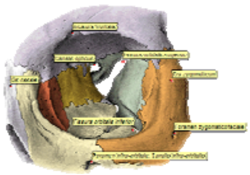


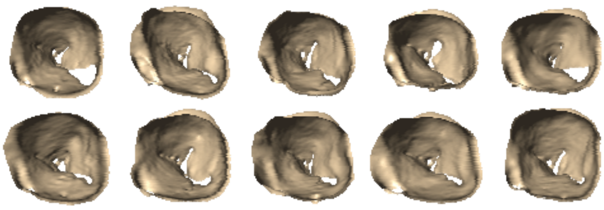


Planning in Cooperation with Dr. Kontio, Helsinki

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 86/76

A Statistical Shape Model of the Orbit





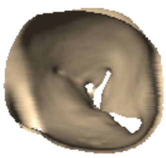
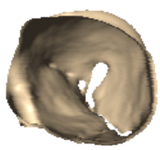
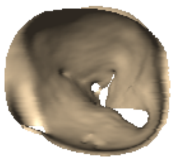
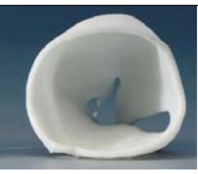
Lamecker H, L Kamer, A Wittmers, S Zachow, Th Kaup, A Schramm, H Noser, B Hammer:
A method for the three-dimensional statistical shape analysis of the bony orbit.
Proc. Computer Aided Surgery around the Head, pp. 94-97 (2007)

Kamer L, H Noser, H Lamecker, S Zachow, A Wittmers, Th Kaup, A Schramm, B Hammer:
Three-dimensional statistical shape analysis -- A useful tool for developing a new type of orbital implant?
AO Development Institute, New Products Brochure 2/06, pp. 20-21 (2006)

Therapy Planning
in Orbit-Surgery

Vis08 VIS • INFOVIS • VAST

Template for Custom Implant Design

	mean	first mode of variation (min/max)	
statistical model			
rapid prototyping			

Cooperation with Dr. Noser, AO Development Institute, Davos, Switzerland

Therapy Planning in Rhinosurgery

VIS08 VIS • INFOVIS • VAST

Esthetics & Function

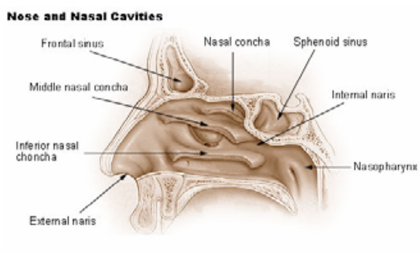
www.zib.de/visual/projects/nose

Therapy Planning in Rhinosurgery

VIS08 VIS • INFOVIS • VAST

Function of the Nose

- Breathing - Smelling
- Cleaning the air
- Conditioning the air to body temperature
- Humidification



Surgical correction might be indicated

in cases where the function is disturbed, e.g. due to any obstruction or deformity.

Therapy Planning in Rhinosurgery

Vis08 VIS • INFOVIS • VAST

Dysfunction of the Nose

- Septal deviation
- Deformities of the external nose
- Paranasal sinusitis, nasal polyps

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 91/76

Therapy Planning in Rhinosurgery

Vis08 VIS • INFOVIS • VAST

Understanding Nasal Airflow

- Characterization of typical airflow phenomena
- Analysis of the correlation between shape and function of the nose
- Individualized therapy planning of rhinosurgery under consideration of *regular* nasal air flow

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 92/76

Therapy Planning in Rhinosurgery

Understanding Nasal Airflow

Due to the complexity and the anatomical inaccessibility of the nasal cavities, as well as the limited availability of meaningful measuring methods

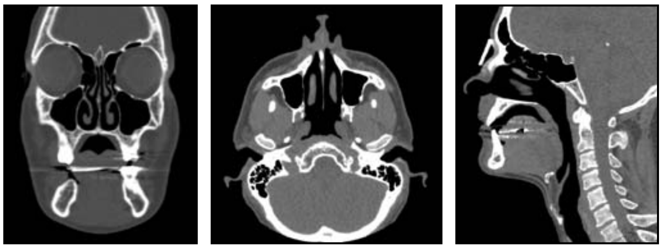
Modeling and simulation of nasal airflow via Computational Fluid Dynamics (CFD)

IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 93/76

Therapy Planning in Rhinosurgery

A Reference Model of the Nasal Airways

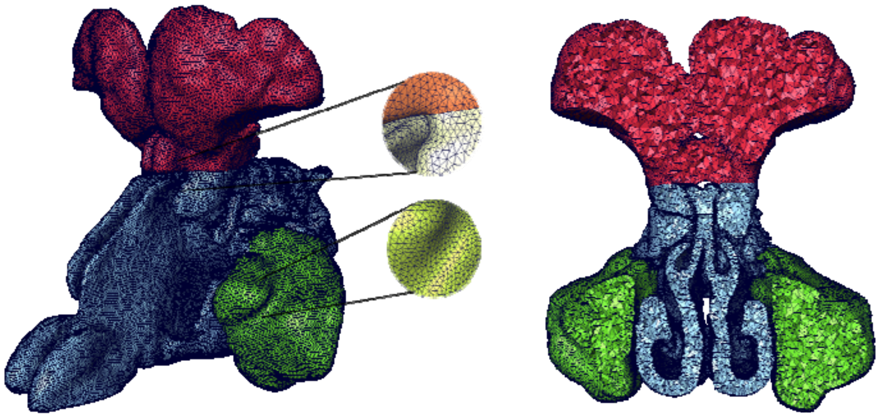
- Helical CT scan (64-slice) of a volunteer
- Local administration of a decongestant (xylometazoline)
- Systemic application of methylprednisolon



IEEE Visualization 2008 Stefan Zachow: Simulation & Visualization for Surgical Planning 94/76

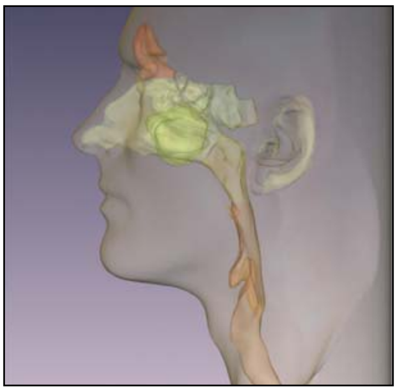
Therapy Planning in Rhinosurgery

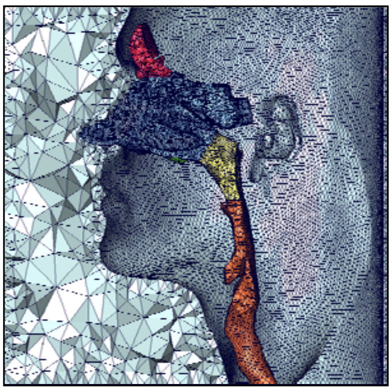
A Reference Model of the Nasal Airways



Therapy Planning in Rhinosurgery

Upper Respiratory Tract and Inflow Region

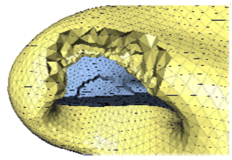




Boundary conditions

Walls (mucosa)

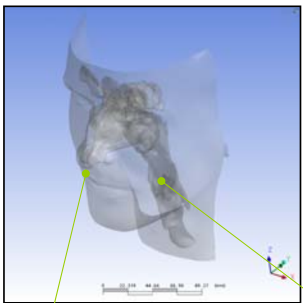
- smooth
- flow involved friction



Air

- isothermal, incompressible
- density 1.185 kg/m^3
- dynamic viscosity 1.831 e^{-5} kg/m·s
- temperature 25 °C
- ambient pressure (absolute) 101325 Pa

Boundary conditions



Outlet: trachea

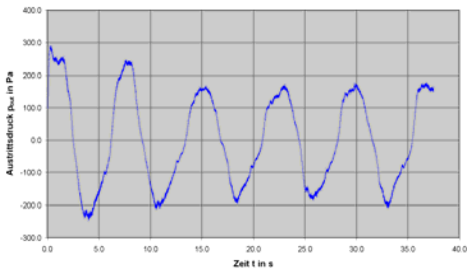
Nostril 0 Pa

Steady state

- Outlet pressure = -150 Pa

Transient flow

- Time dep. pressure: Active Anterior Rhinomanometry (AAR)



Computational Fluid Dynamics

- **Conservation of mass**

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0$$

- **Conservation of momentum**

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right)\right) + f_i$$

- **Conservation of energy**

$$\frac{\partial(\rho E)}{\partial t} + \frac{\partial(\rho u_j E)}{\partial x_j} = -\frac{\partial(p u_j)}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j}\right) + \frac{\partial(u_i \tau_{ij})}{\partial x_j} + S_E$$

Therapy Planning in Rhinosurgery

Computational Fluid Dynamics

- **Transport equations**

  (Reynolds-averaged) Navier-Stokes PDE

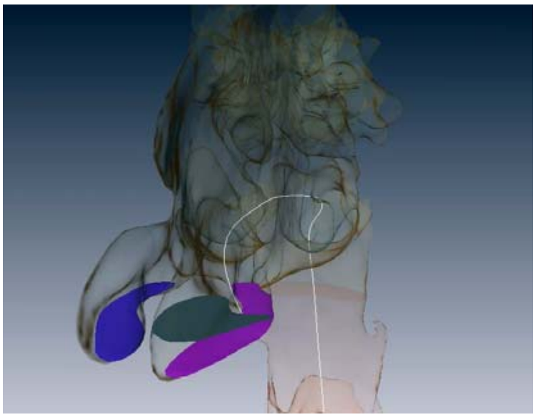
$$\underbrace{\frac{\partial}{\partial t}(\rho\Phi)}_{\text{time alteration rate}} + \underbrace{v_j \frac{\partial}{\partial x_j}(\rho\Phi)}_{\text{convective transport}} = \underbrace{\Gamma_\Phi \frac{\partial^2 \Phi}{\partial x_j^{\,2}}}_{\text{diffusive transport}} + \underbrace{S_\Phi}_{\text{production}}$$

Numerical solution of the averaged conservation equations (velocity and pressure field)

Ansys CFX ®

Therapy Planning in Rhinosurgery

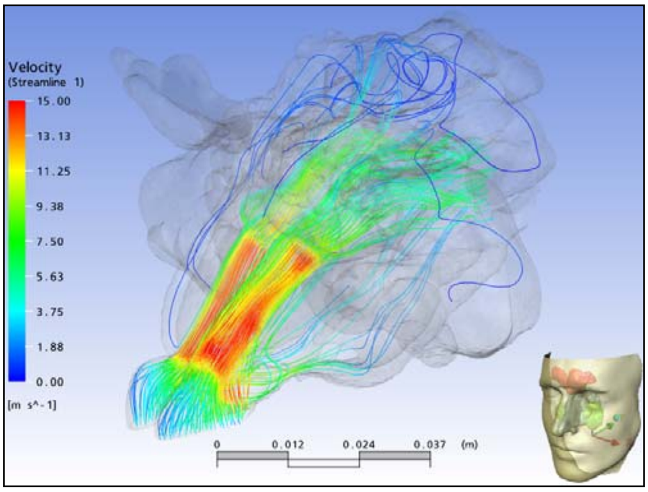
Vis08 VIS • INFOVIS • VAST



Movie: Hydraulic profile of the upper respiratory tract

Therapy Planning in Rhinosurgery

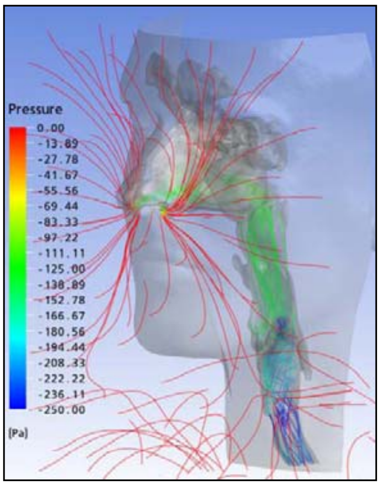
Vis08 VIS • INFOVIS • VAST



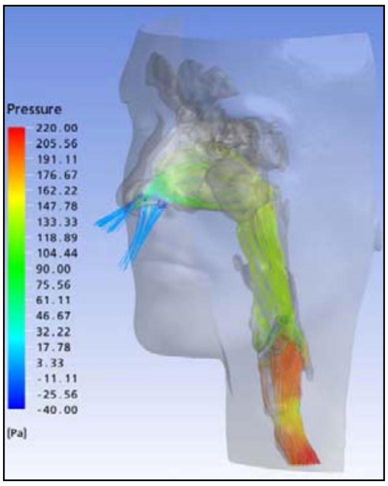
Visualization of inspiratory flow up to 16 m/s under laminar and turbulent conditions

Therapy Planning in Rhinosurgery

Vis08 VIS • INFOVIS • VAST



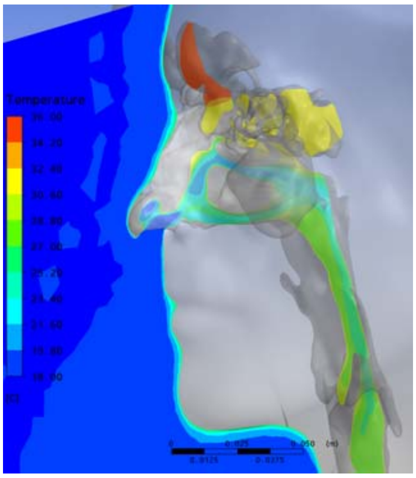
inhalation



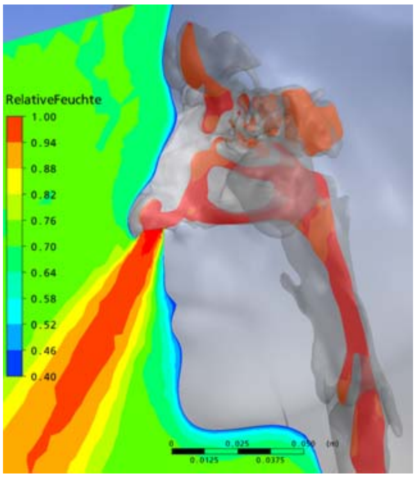
exhalation

Therapy Planning in Rhinosurgery

Vis08 VIS • INFOVIS • VAST

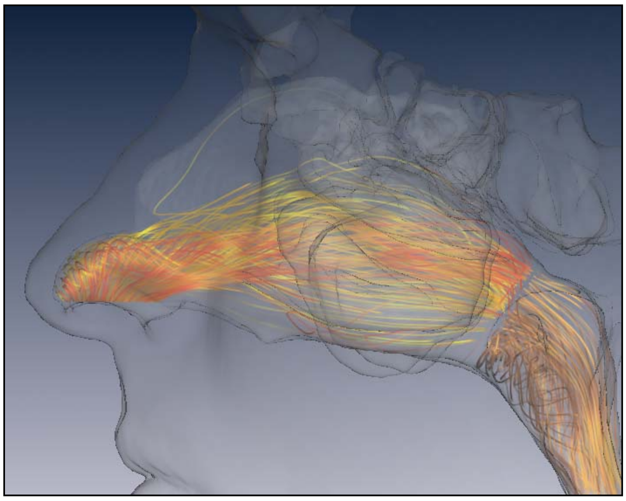


Inhalation (temperature)



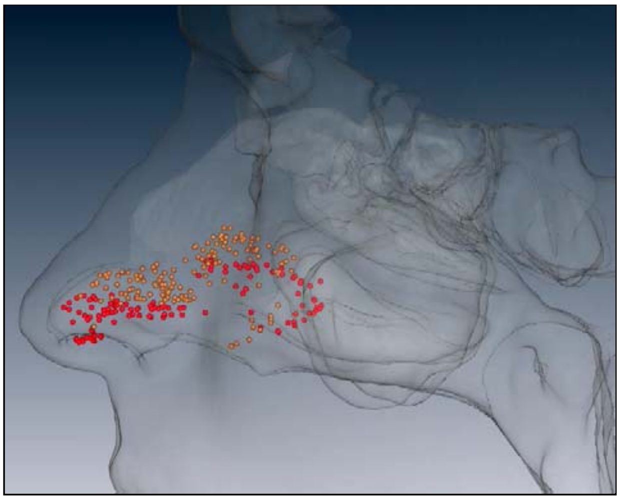
Exhalation (humidity)

Therapy Planning in Rhinosurgery



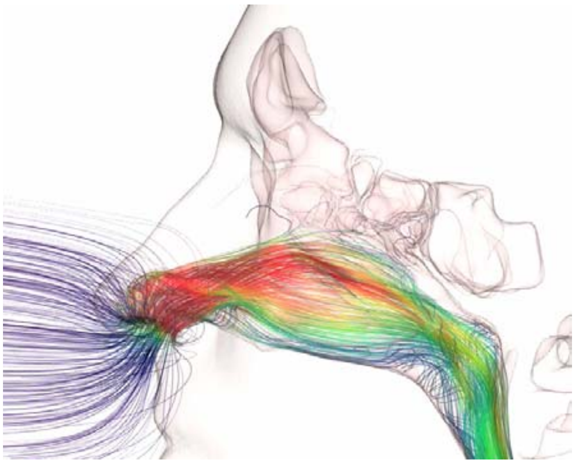
Illuminated streamline visualization of the velocity vector field with color coded discrimination of left (red) and right (gold) side

Therapy Planning in Rhinosurgery



Movie: Particles - color coded discrimination of left (red) and right (gold) side

Therapy Planning in Rhinosurgery

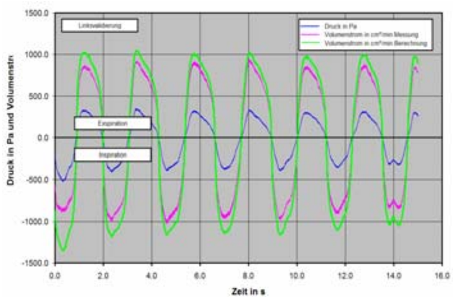


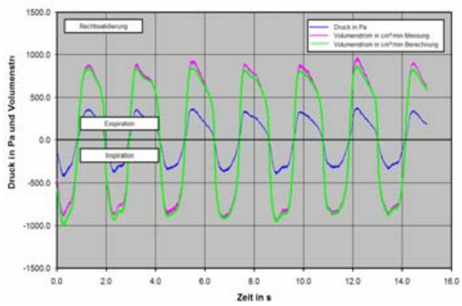
Movie: Inhalation and exhalation with velocity coded streamlines

Therapy Planning in Rhinosurgery

Validation (pressure / time)

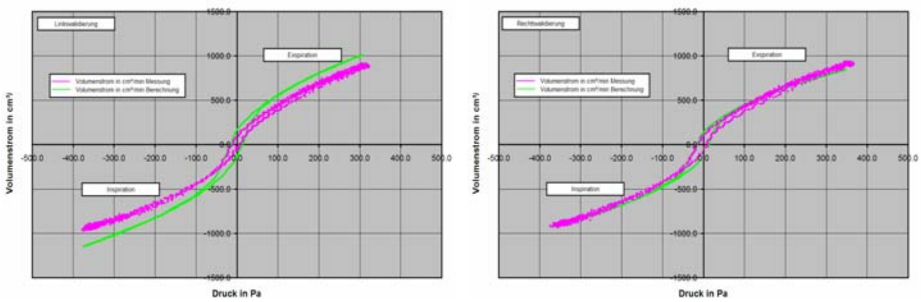
Simulation vs. Measurements (left/right nostril)



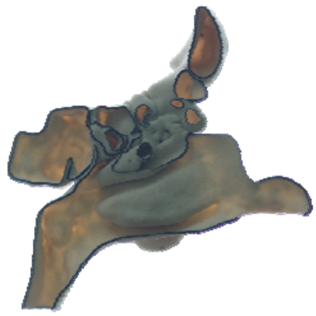


Validation (total flow / pressure)

Simulation vs. Measurements (left/right nostril)



Biofluidmechanics (experimental studies)



Zachow S, A Steinmann, Th Hildebrandt, W Heppt:
Understanding nasal airflow via CFD simulation and visualization.
Proc. Computer Aided Surgery around the Head, pp. 173-176 (2007)

Zachow S, A Steinmann, Th Hildebrandt, R Weber, W Heppt:
CFD Simulation of nasal airflow: Towards treatment planning for functional rhinosurgery.
Int. J. of Computer Assisted Radiology and Surgery, Springer, pp. 165-167 (2006)