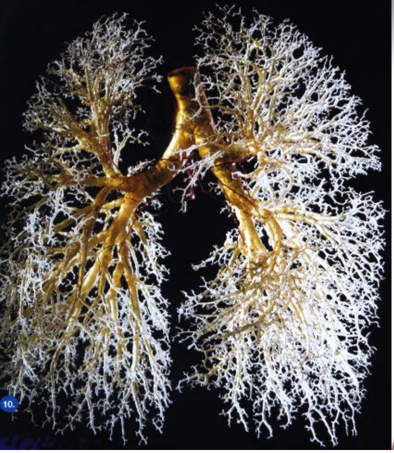

Biological and Medical Fluid Mechanics I

1. Introduction

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1.1.1 Exchange of respiratory gases

Purpose: interchange of gases

Differentiation between

- upper airways: **nose**, throat, larynx, (trachea)
- lower airways: (trachea), **lungs**

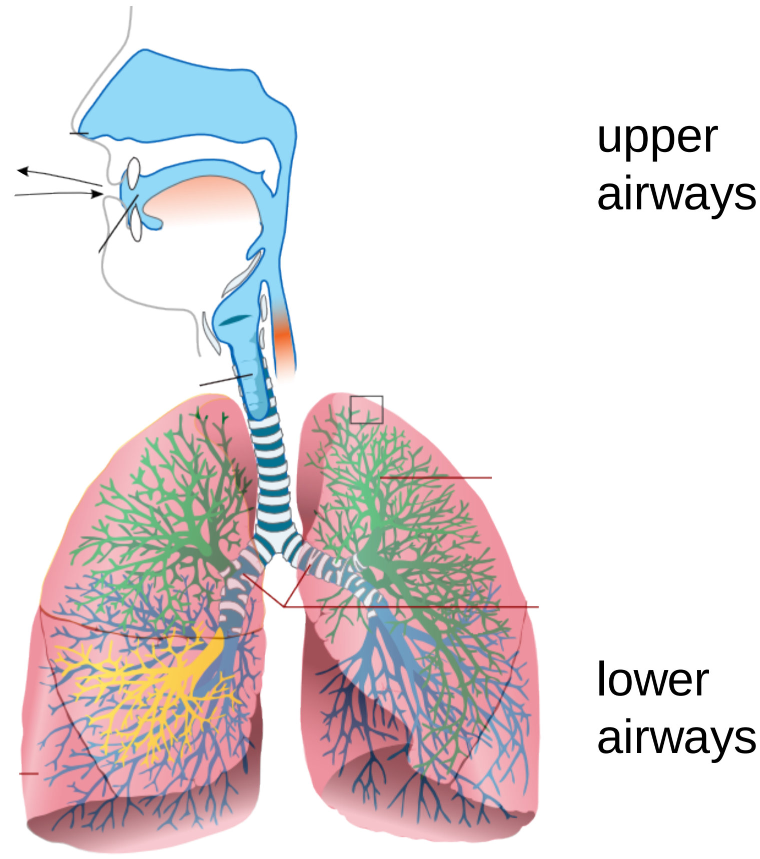

Fig.1.1: Upper and lower airways [1]

1.1.1 Exchange of respiratory gases

Nose: Components

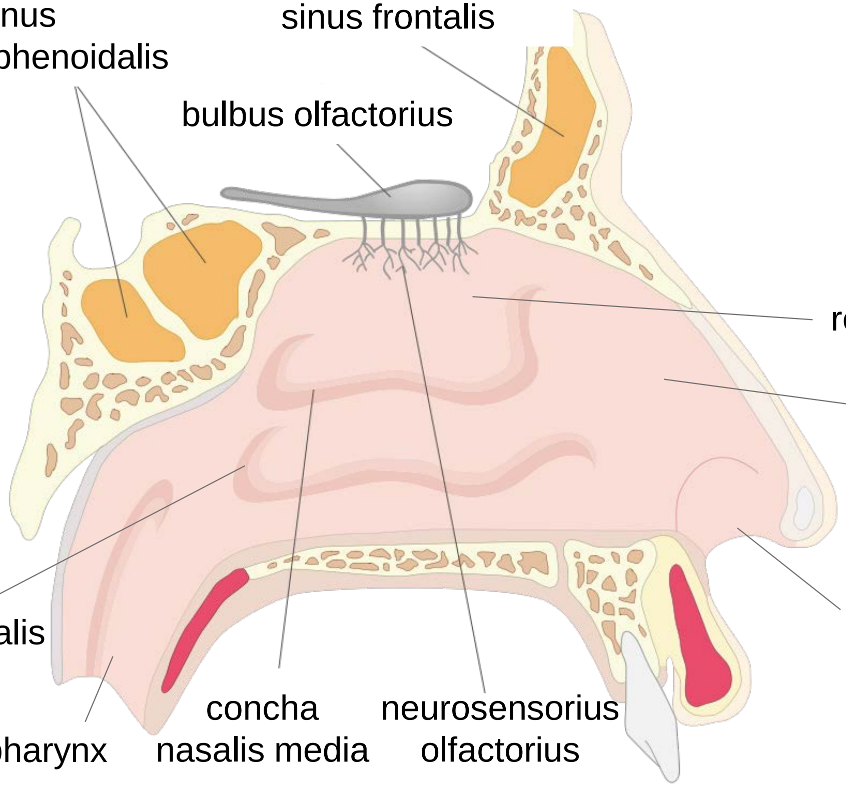

Fig.1.2: Sagittal section of the nasal cavity [2]

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1.1.1 Exchange of respiratory gases

Nose: Functions and Physiological data [3]

- Sense of Smell (regio olfactoria)
- Tempering air (turbinates)
- Isolation (airfilled cavities)
- Moistening (goblet cells)
- Resonance Organ (paranasal sinuses)
- Cleaning air (ciliated Epithelium)

		medium respiration	maximum respiration
minute ventilation	[1/min]	6-8	50-70
ventilation frequency	[1/min]	15	25
tidal volume	[ml]	400-500	2000-2800

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1.1.1 Exchange of respiratory gases

Lungs

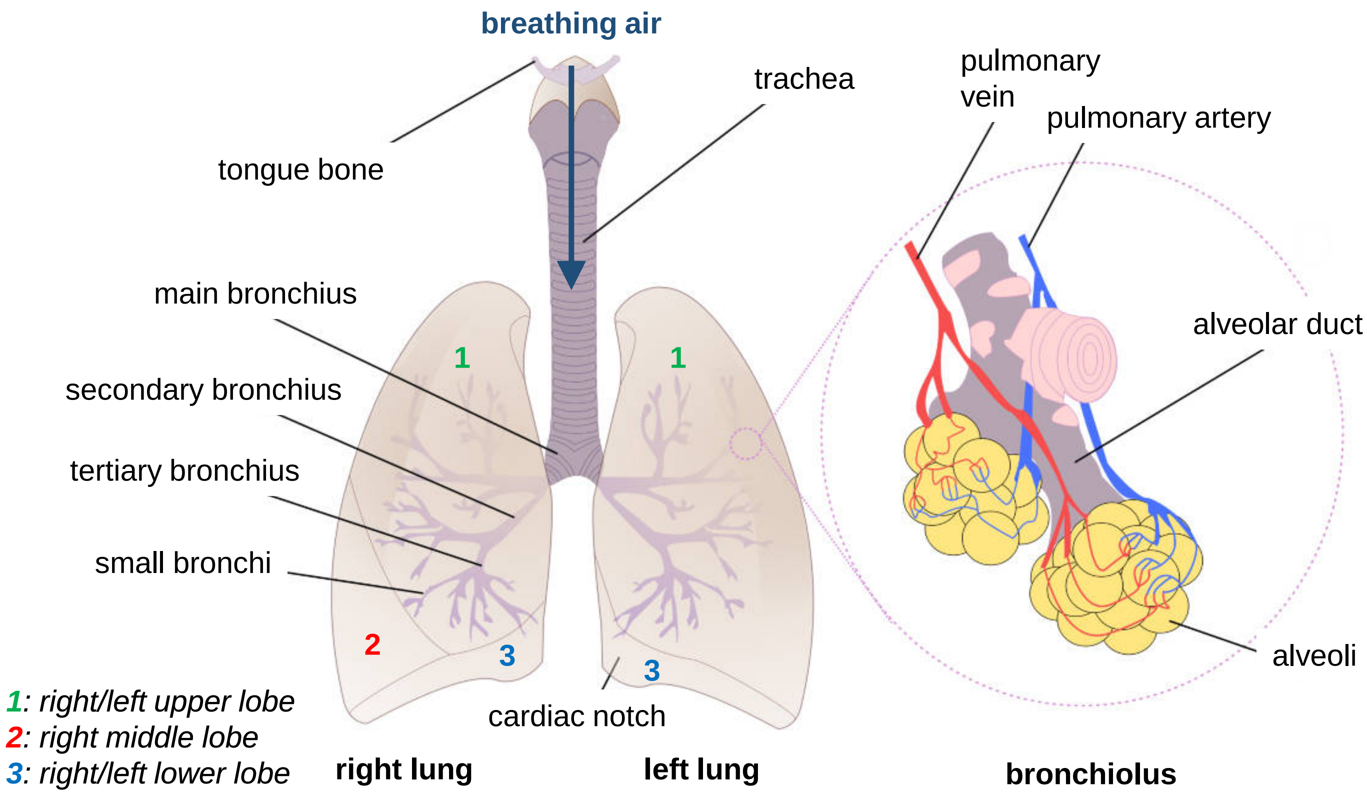

Fig.1.3: Diagram of the lung [4]

1.1.1 Exchange of respiratory gases

Types of Transport

- **Diffusive Transport**
  - in the lungs: alveoli ↔ blood
  - in the capillary system: tissue ↔ blood
- **Convective Transport**
  - to realize large transport distances in higher organisms
  - if diffusion (molecular transport) is too slow

  → blood circulation

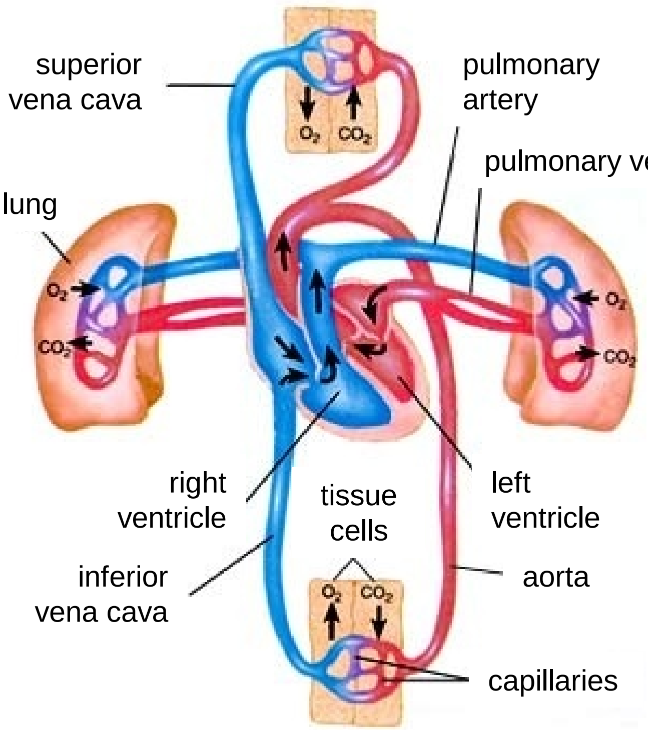

Fig.1.4: Convective and diffusive gas exchange in the human body [5]

1.1.1 Exchange of respiratory gases

Diffusive transport in the lungs

- total surface for gas exchange with blood: 90 to 130 m^2
- basic flow: oscillating (intermittent, alternating)
- gas exchange with blood:
  O^2 in, CO^2 out
- gas exchange with alveoli:
  CO^2 in, O^2 out

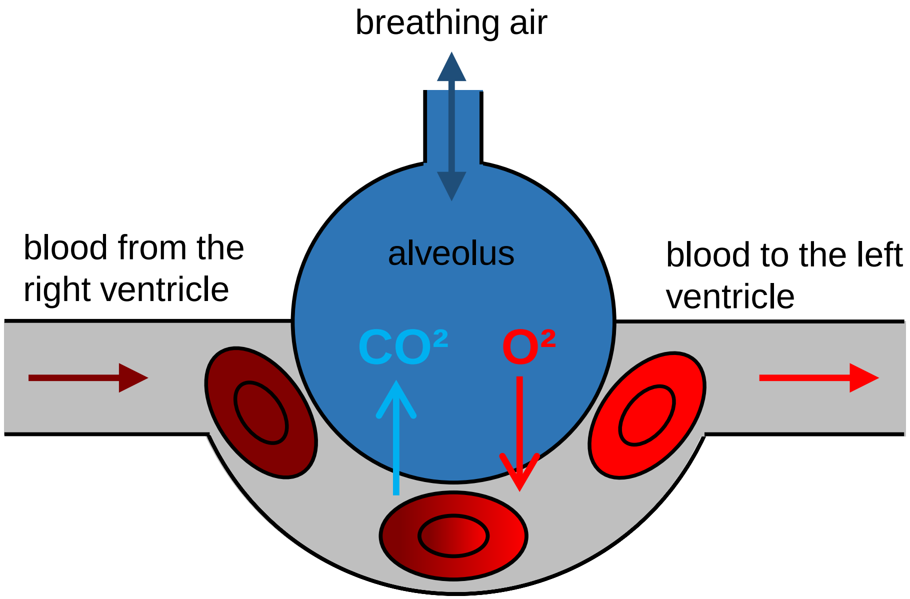

Fig.1.5: Gas exchange with alveoli

1.1.1 Exchange of respiratory gases

Diffusive transport in the capillary system

- gas exchange with blood:
  CO² in, O² out
- gas exchange with tissue:
  O² in, CO² out

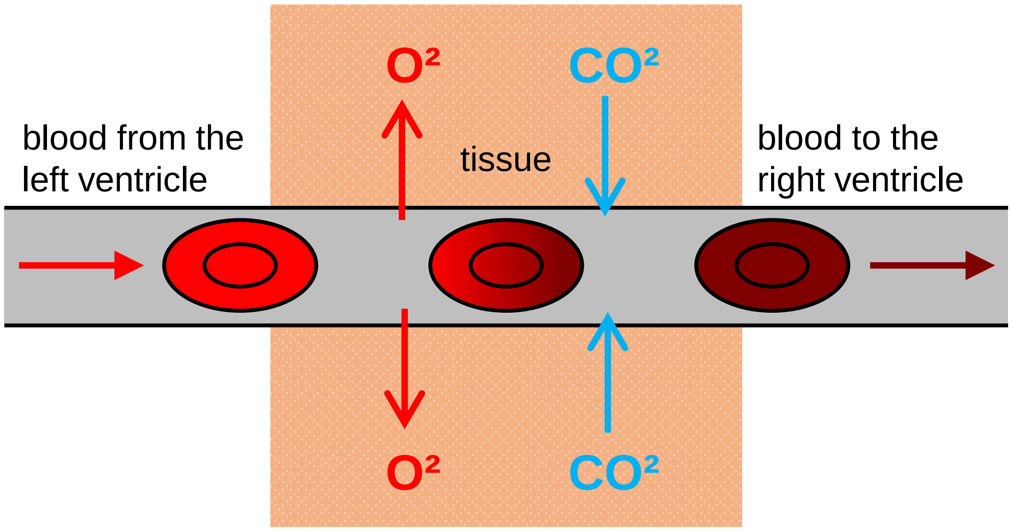

Fig.1.6: Gas exchange with human tissue

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1.1.2 Blood circulation

Tasks

1. Supplying the cells with nutrients (amino acids, electrolytes, …), hormones and gases
2. Regulation of the body temperature
3. Waste disposal for all cells
4. Transport of cells and macromolecules to fight infections, … (immune system)
5. Transport of cells and macromolecules to protect the circulation from injury
6. Perfusion of different organs:

   - lung: 100%
   - heart: 100%
   - brain 15%
   - coronary arteries: 5%
   - kidneys: 20%
   - visceral organs: 35%
   - muscles: 15%
   - skin/skeleton: 10%

1.1.2 Blood circulation

Simplified circulation scheme

- **systematic circulation:**
  left heart → aorta with aortic arc → lower cycle (kidneys, spleen, gastro-intestinal tract, legs)/ upper cycle (lungs, head, arms) → right heart
- **pulmonary circulation:**
  right heart → lungs → left heart
- **arterial system:**
  - cross section of single vessels decreases in direction of the flow
  - total cross section increases
- **venous system:**
  - cross section of single vessels increases in direction of the flow
  - total cross section decreases

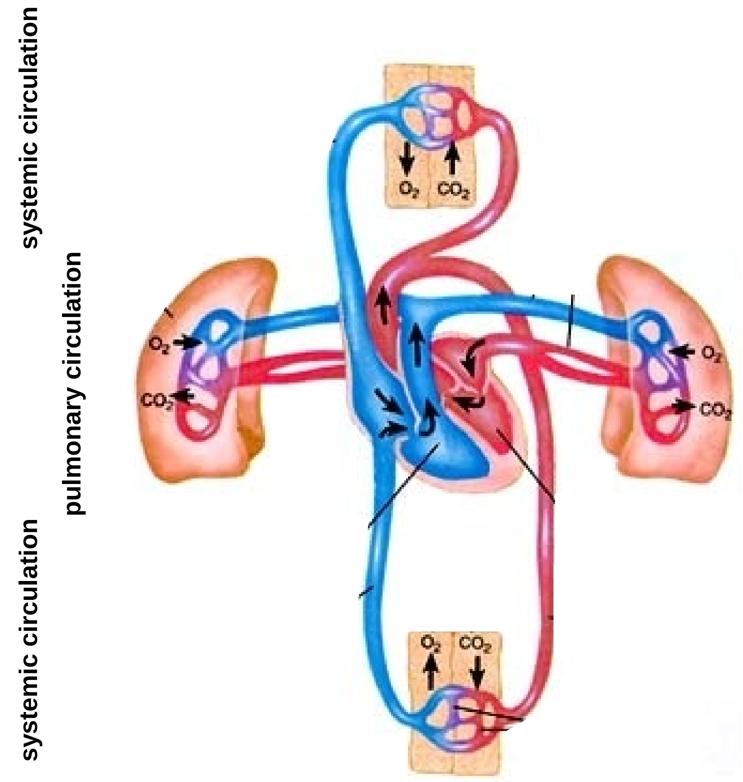
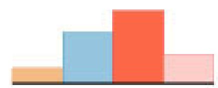
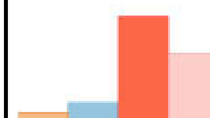
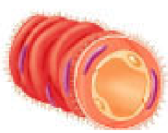
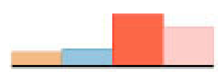
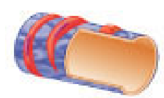
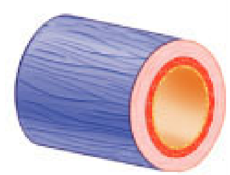
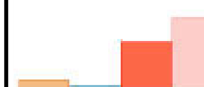


Fig.1.7: The blood circulation system [5]

1.1.2 Blood circulation

Blood Vessel Anatomy

Vessel Type	Average Lumen Diameter (D), Wall Thickness (T)	Relative Tissue Makeup (Endothelium, Elastic Tissues, Smooth Muscles, Fibrous (Collagenous) Tissues)
 Elastic artery	D: 1.5cm T: 1.0mm	
 Muscular artery	D: 6.0mm T: 1.0mm	
 Arteriole	D: 37.0µm T: 6.0µm	
 Capillary	D: 9.0µm T: 0.5µm	
 Venule	D: 20.0µm T: 1.0µm	
 Vein	D: 5.0mm T: 0.5mm	

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1.1.3 Other transportation processes

- **Upper-intestinal tract (mouth, esophagus):**
  - peristaltic transport (swallowing)
- **Gastrointestinal tract (stomach, intestines):**
  - flat waves for mixing, occasional steep waves to push the food forward
- **Kidneys:**
  - peristaltic transport of the urine

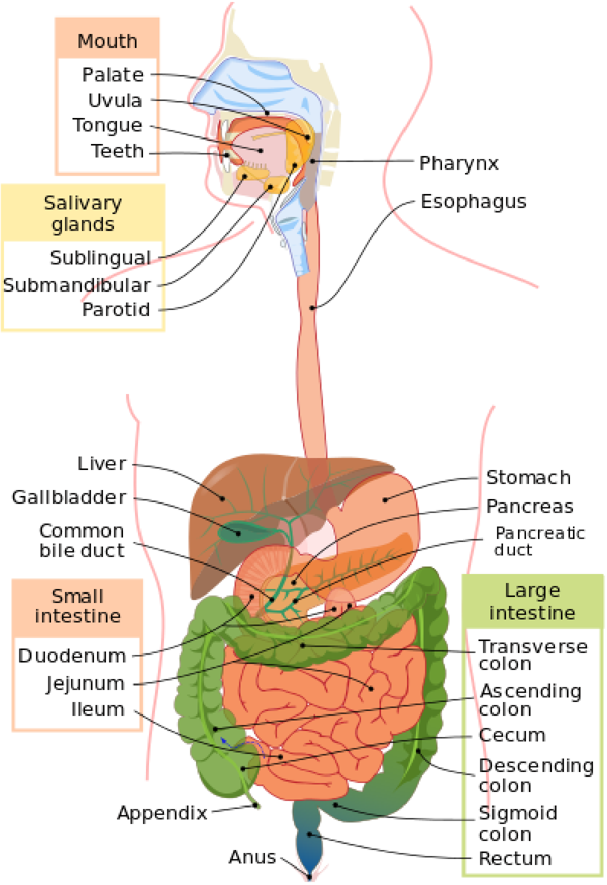

Fig.1.8: Schematic upper- and gastrointestinal tract [6]

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1.2 Transportation processes in medical devices

General purpose: temporary or permanent substitution or function support of organs and parts of organs

Examples

- **Blood Pump:** heart substitute/support in heart lung machines
- **Oxygenator:** artificial lung
  - **Bubble Oxygenator:** air blowing or O_2 pearling from below through the blood
  - **Plate Oxygenator:** rotating plates are immersed in blood
  - **Membrane Oxygenator:** capillary Oxygenator, thin membrane separates blood from gas
- **Haemodialysis:** artificial kidney
  - problem: differentiation between toxic and useful materials for the body
  - two concepts:
    1. Filtration und Ultra-Filtration
    2. Dialysis: Transport through permeable “solubility-membrane”
- **Hemoperfusion**
- **Artificial heart valves, hearts, veins, ureter, anti-reflux valve**
- **Devices for therapeutic purposes**

1.2 Transportation processes in medical devices

Fig. 1.9: Oxygenators

Fig. 1.10: Artificial vessel (left) , Artificial heart (right)

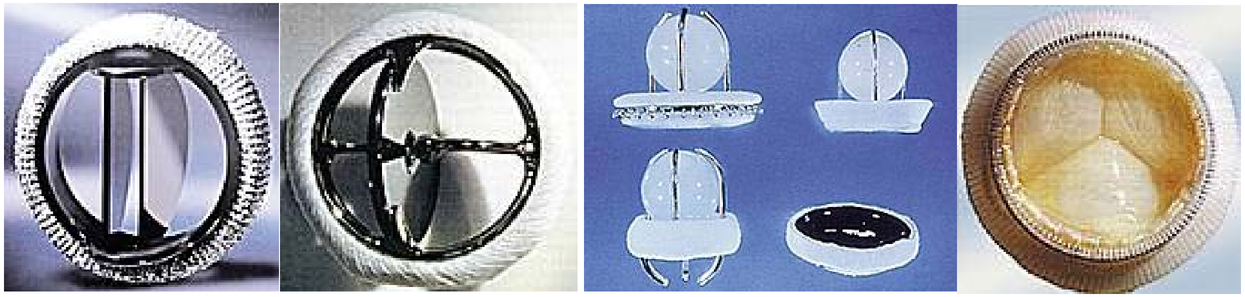

Fig. 1.11: Artificial heart valves (left to right): flap valve, tilt valve, ball valve, bio-prothesis valve

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1.3 Tasks of fluid mechanics in medicine

General tasks: determination of

- pressures
- flow structures
- transport mechanisms
- influences on heat and mass transfer
- rheological behavior of the flow medium

Development of artificial organs

- heart valves, blood pumps, oxygenators, artificial kidneys, …
- the greatest problem: blood
  - → dead water regions
  - → flow separation
  - → high shear stress
  - → thrombus formation

1.3 Tasks of fluid mechanics in medicine

Special characteristics of flows in the human body

- **rheological properties:**
  - blood → non-Newtonian fluid
  - intestine content → Bingham-fluid
- **flow profiles:**
  - pulsating → acceleration and deceleration effects
  - respiration
  - peristaltic transport (esophagus, stomach, intestine canal, ureters)
- **vessel walls:**
  - elastic
  - actively contracting
  - continuous change of the cross section
  - change of the mechanical properties
- **vessel bifurcations: (lung airways, blood vessels)**
  - continuous change of the velocity profile
  - flow separation at daughter branches
  - secondary flows

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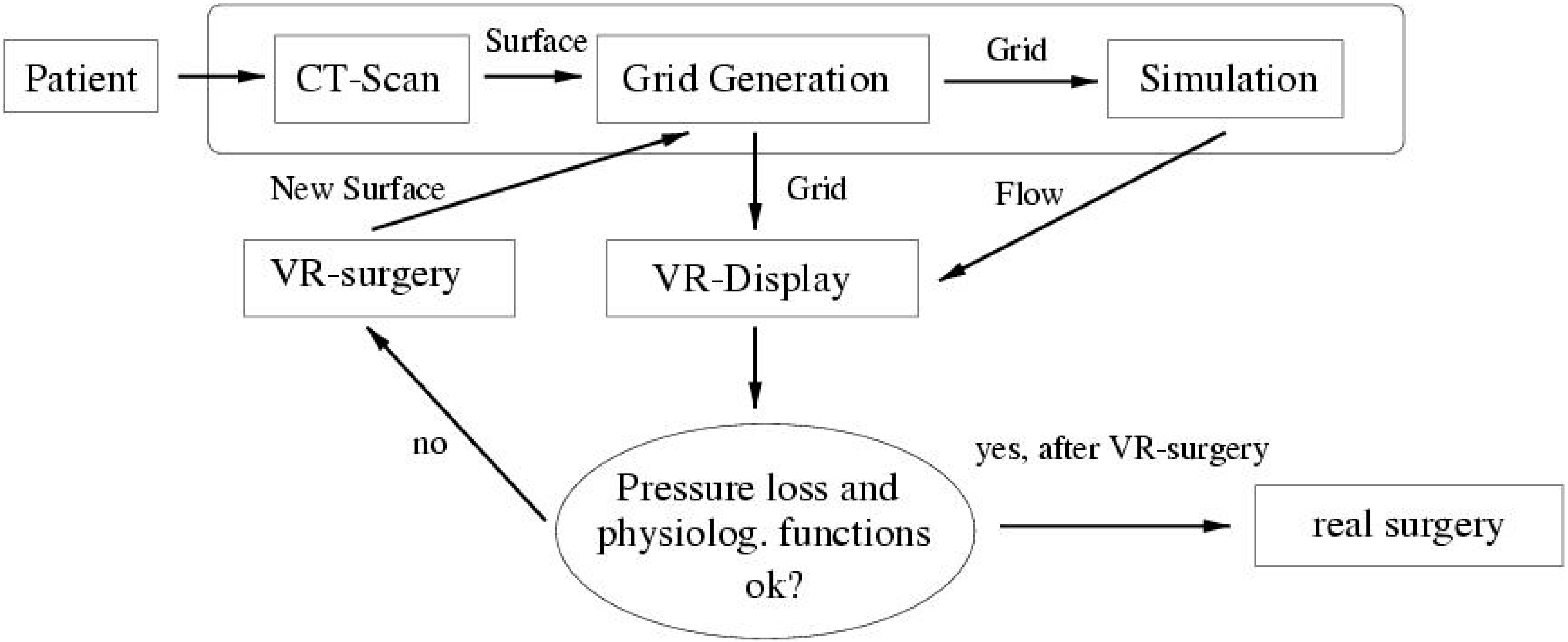
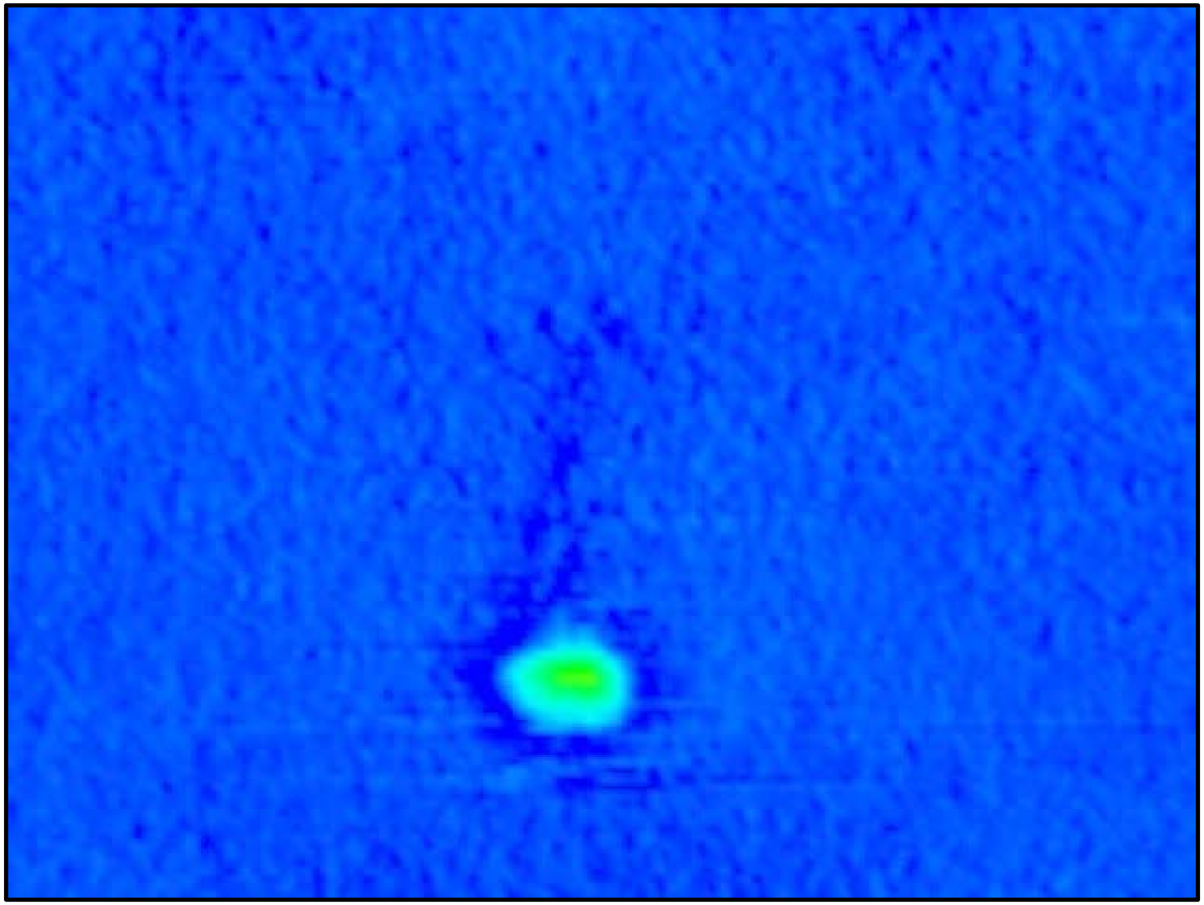
1.4.1 Computer assisted surgery of the nose



1.4.1 Computer assisted surgery of the nose

Computer Tomography of the nasal cavity



1.4.1 Computer assisted surgery of the nose

Computer Tomography of the nasal cavity in 3D

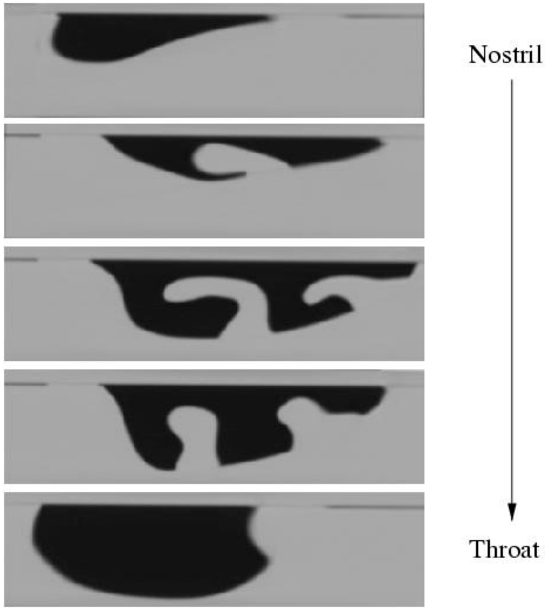
Computer Tomography

of

Human Nasal Cavity

1.4.1 Computer assisted surgery of the nose

Surface Extraction by Computer Tomography



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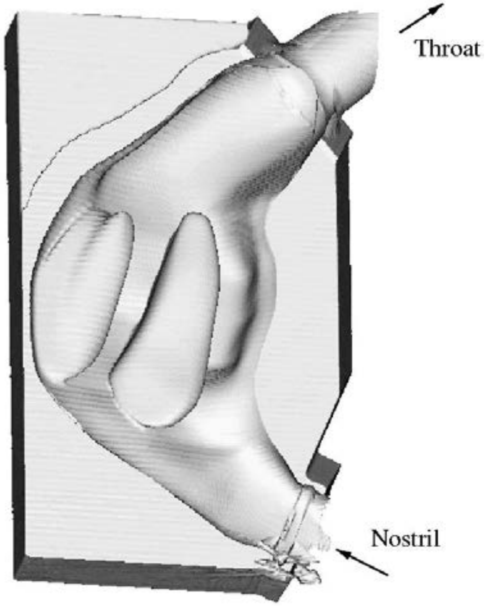
Marching Cube Algorithm

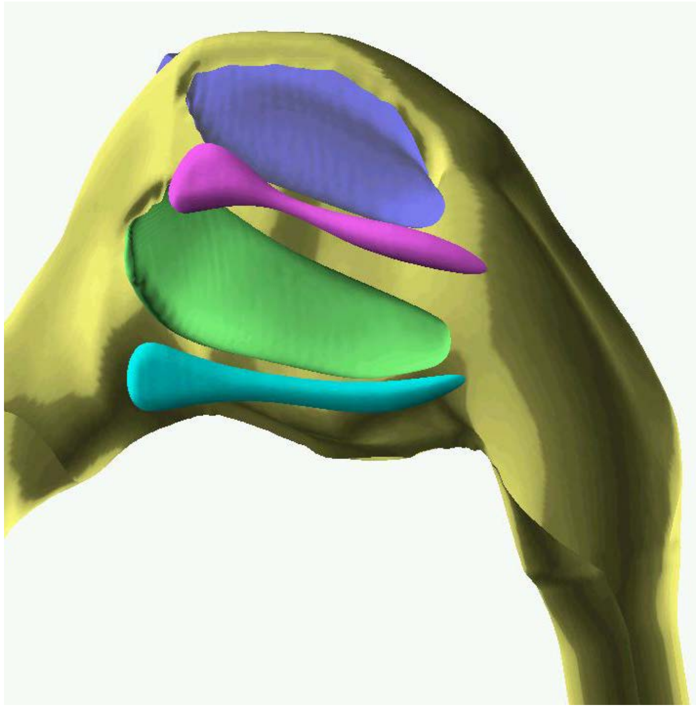


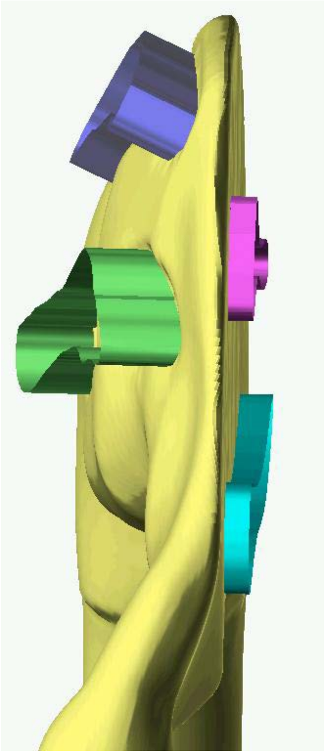
- 300 Cuts, 1mm spacing
- DICOM format
- 512 × 512 × 2 Bytes per cut

- Unstructured surface
- 749.681 nodes
- 1.499.065 triangles

1.4.1 Computer assisted surgery of the nose

Modular surfaces - upper and lower turbinate and spurs





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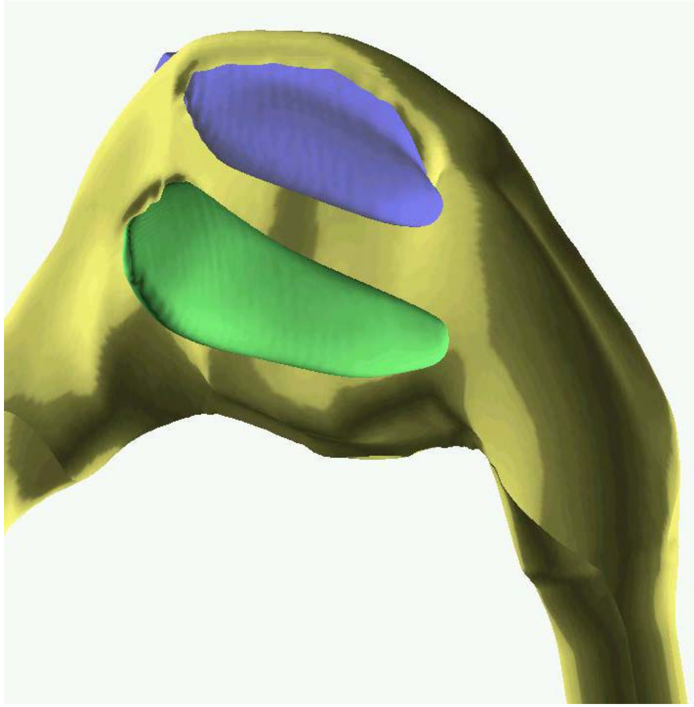
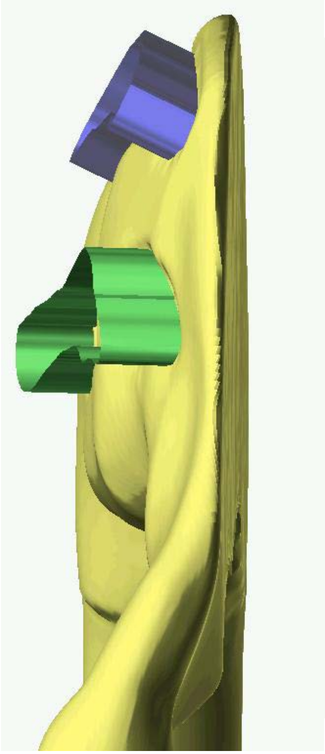
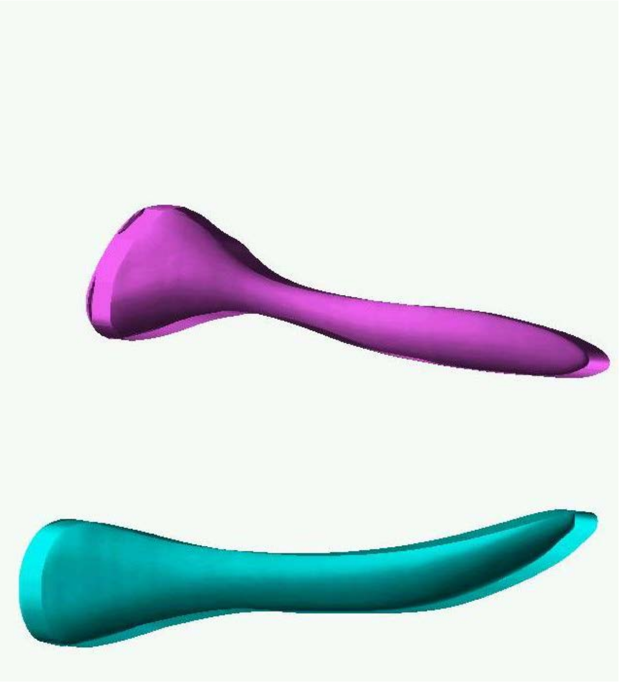
1.4 Examples of application

1.4.1 Computer assisted surgery of the nose

Modular surfaces - upper and lower turbinate



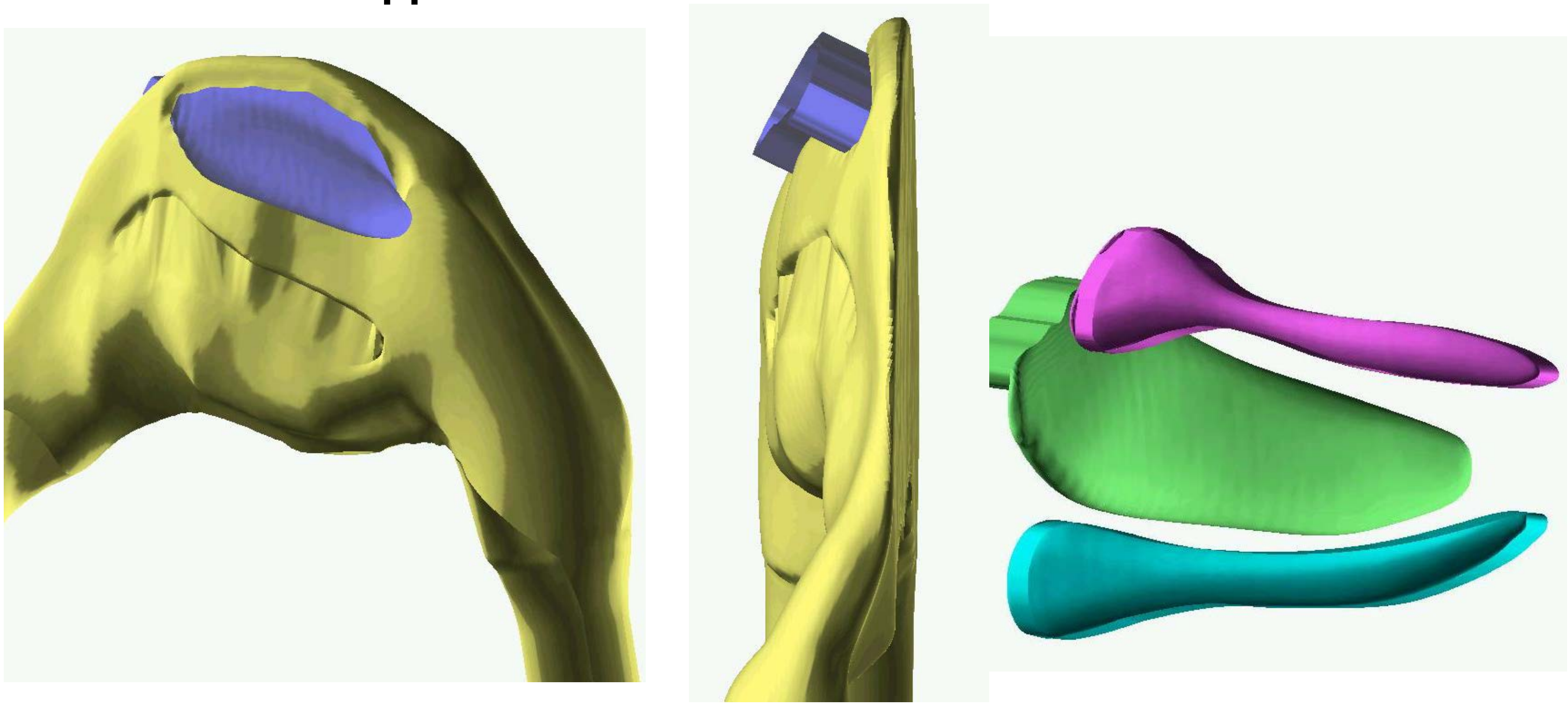




1.4 Examples of application

1.4.1 Computer assisted surgery of the nose

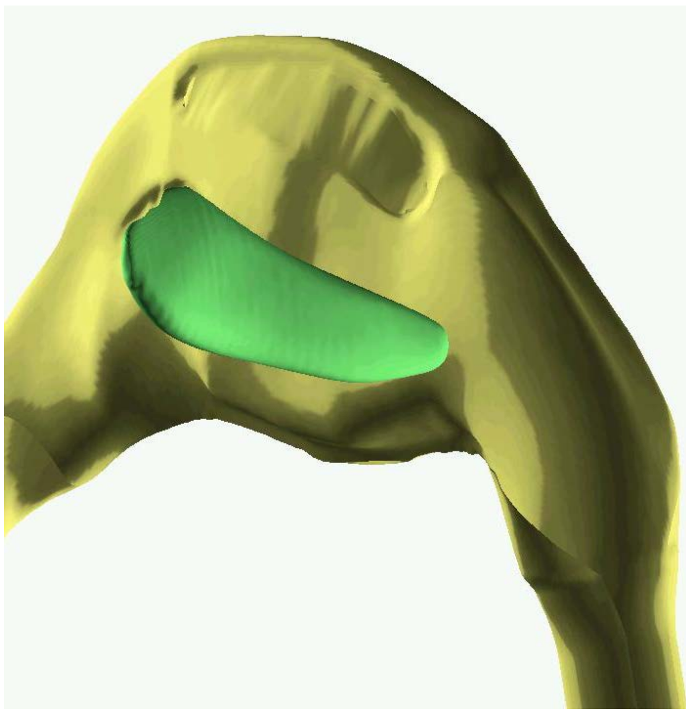
Modular surfaces - upper turbinate

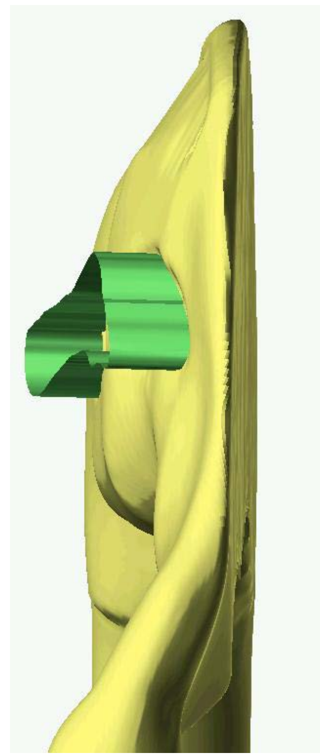


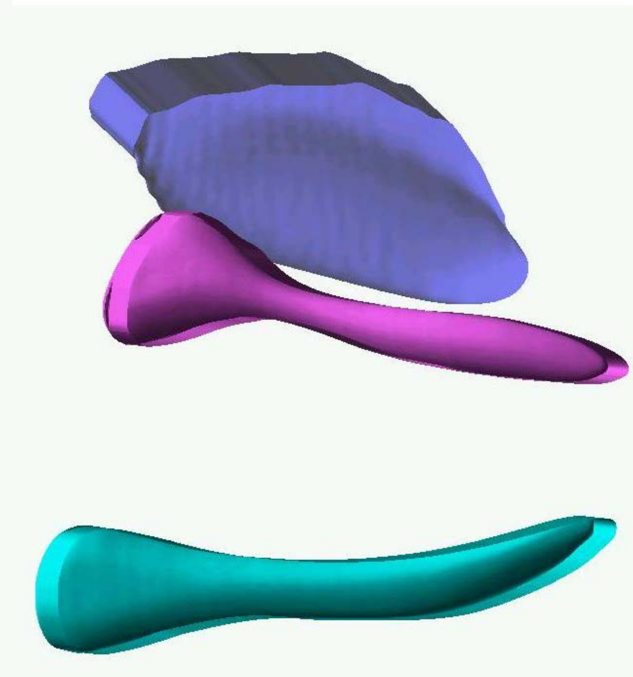
1.4 Examples of application

1.4.1 Computer assisted surgery of the nose

Modular surfaces - lower turbinate



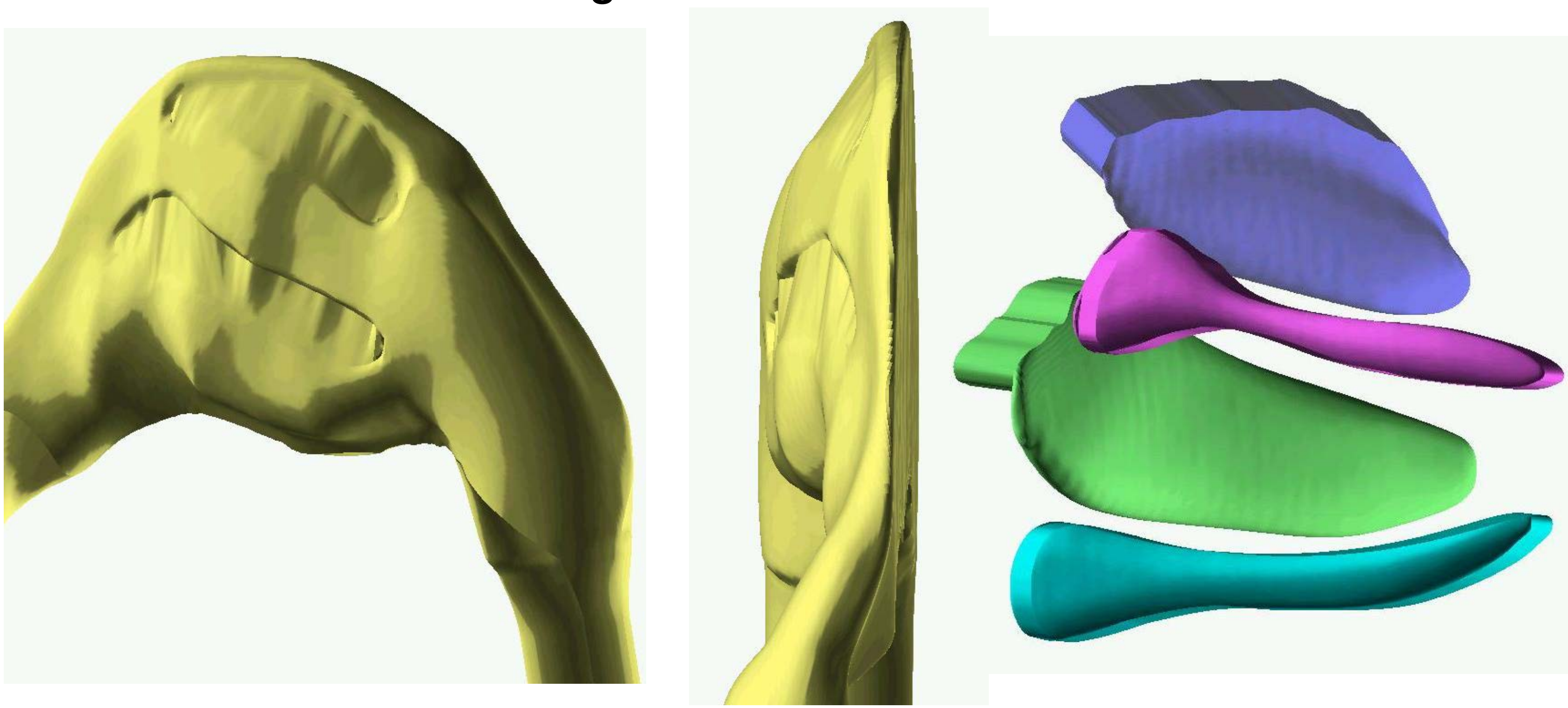




1.4 Examples of application

1.4.1 Computer assisted surgery of the nose

Modular surfaces - clean configuration



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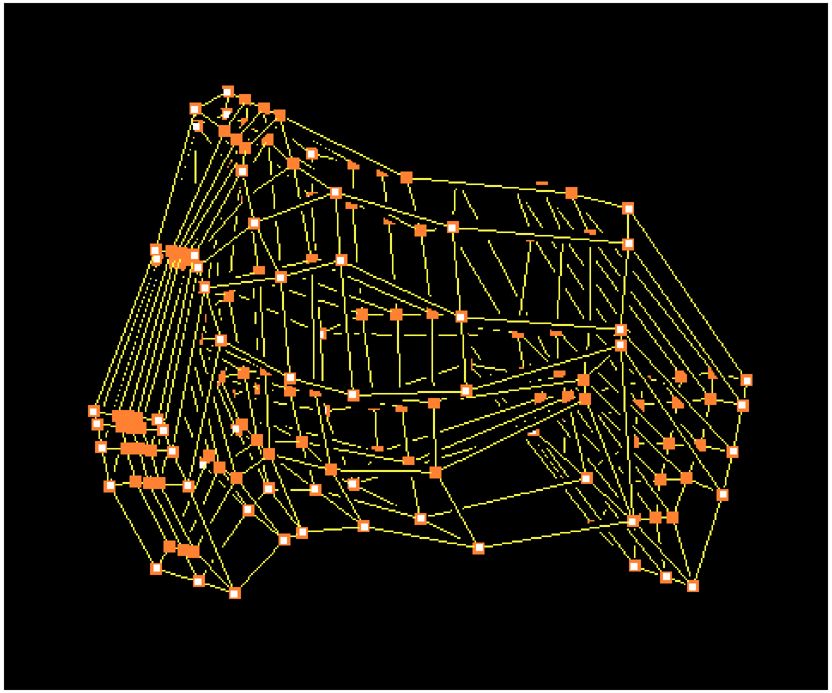
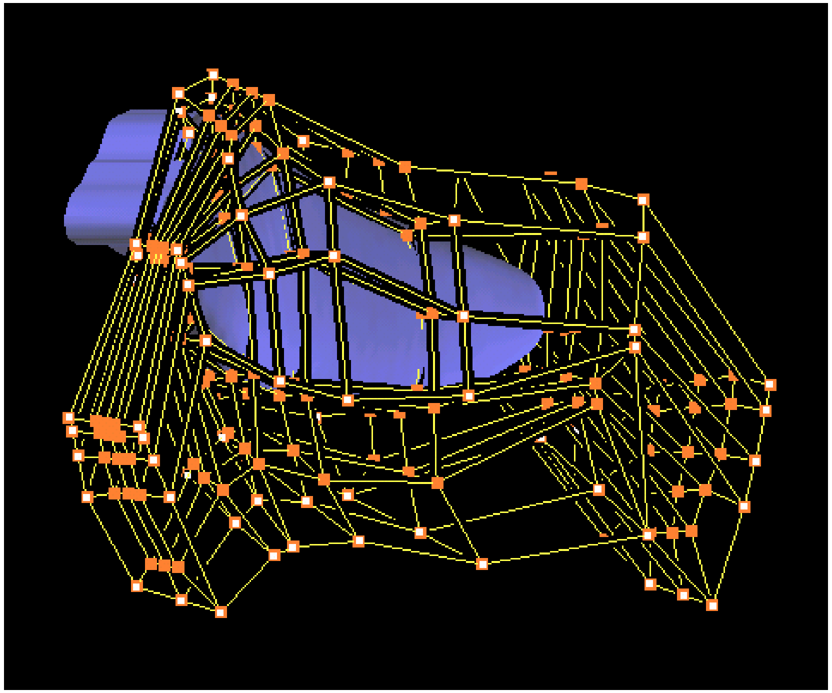
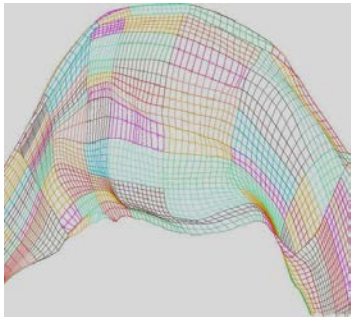
1.4.1 Computer assisted surgery of the nose

Topology module with and without lower turbinate

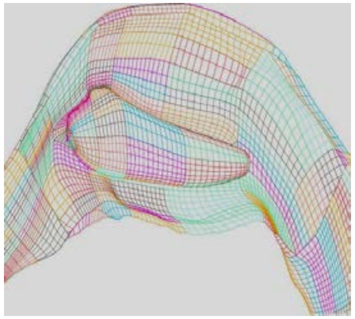
 

1.4.1 Computer assisted surgery of the nose

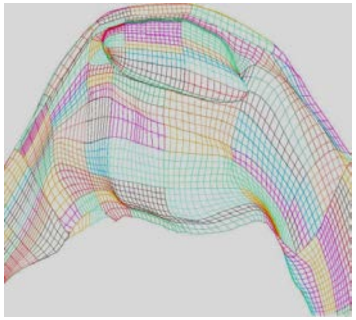
Grids



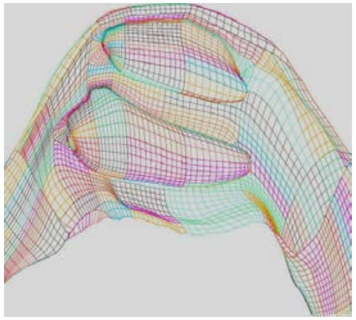
clean



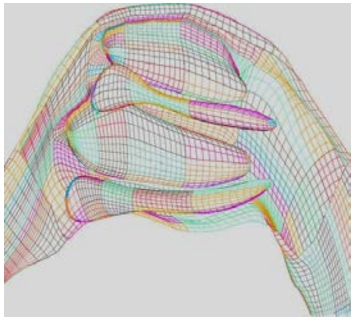
clean + lower turbinate



clean + upper turbinate



clean + upper and lower turbinate



clean + upper and lower turbinate + spurs

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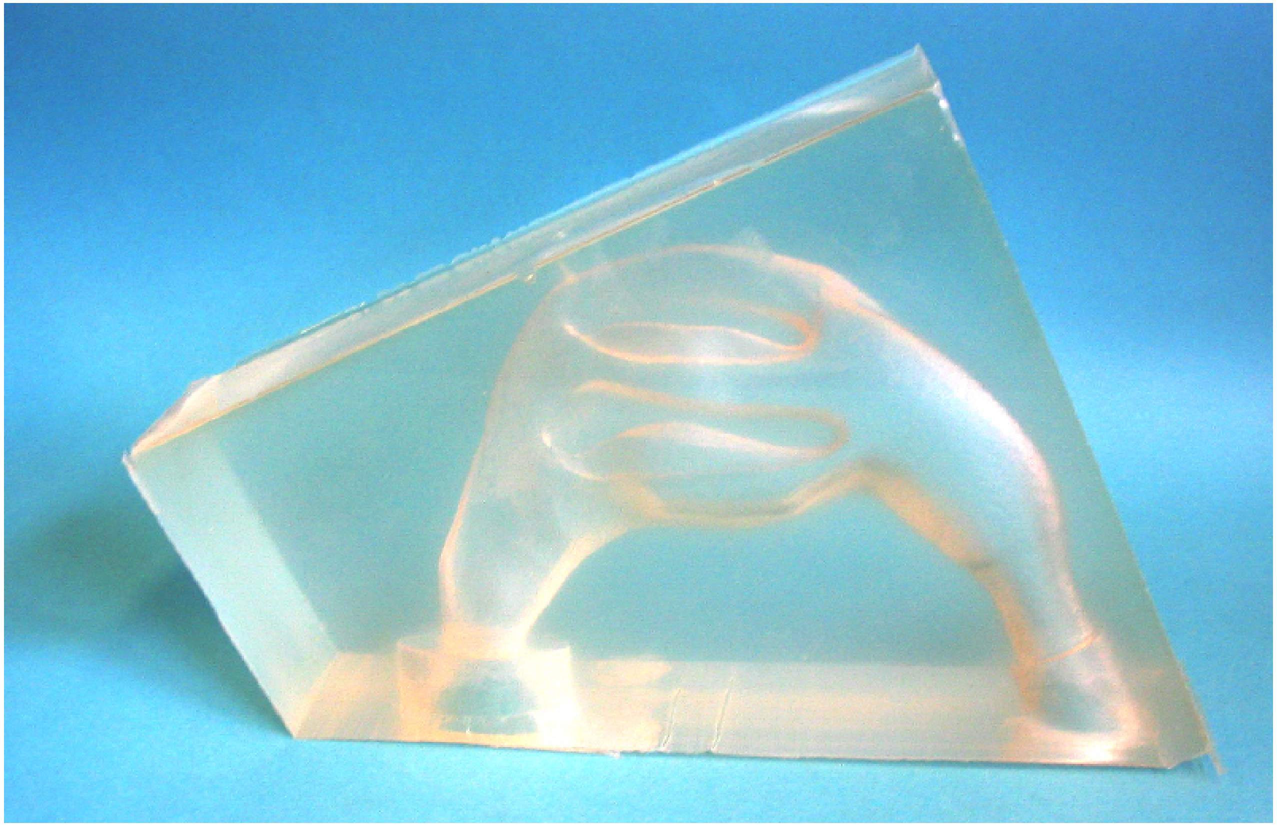
1.4.1 Computer assisted surgery of the nose

Silicone nose model



1.4.1 Computer assisted surgery of the nose

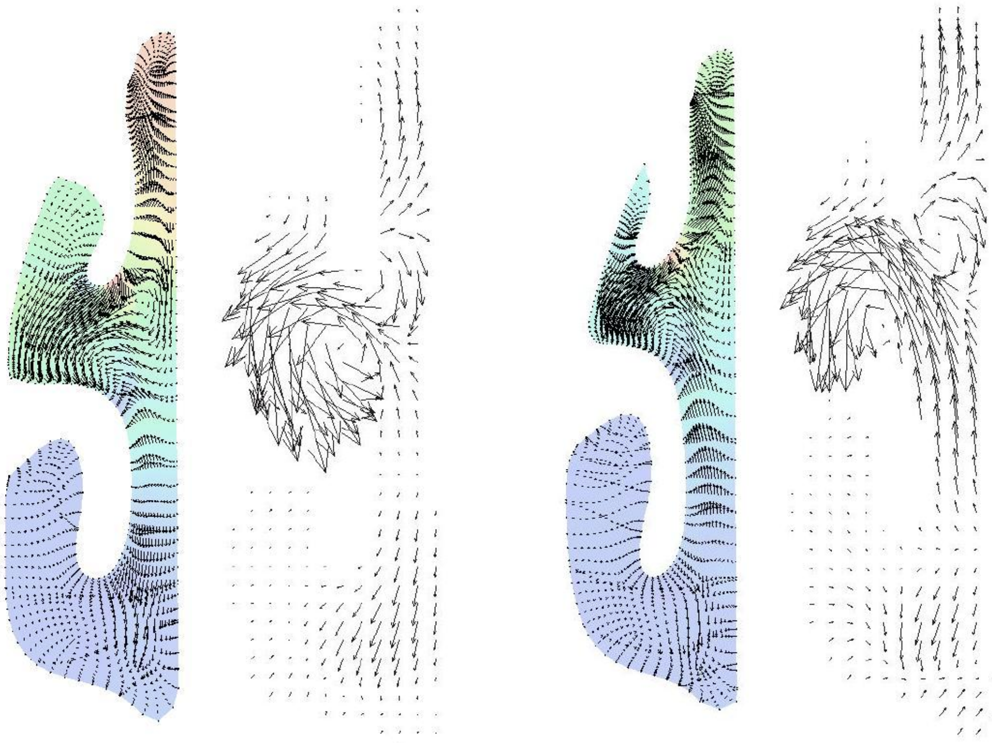
Methods and scopes

- **numerical simulation:**
  - solution of the Navier-Stokes equations based upon a finite volume method
- **experimental investigation:**
  - quantitative measurement of the velocity field using Particle-Image Velocimetry
- **scopes/open questions:**
  - laminar or turbulent flow?
  - influence of the geometry?
  - steady or unsteady flow?

1.4.1 Computer assisted surgery of the nose

Results: Comparison of numerics and experiments - Inhalation

cross section 1

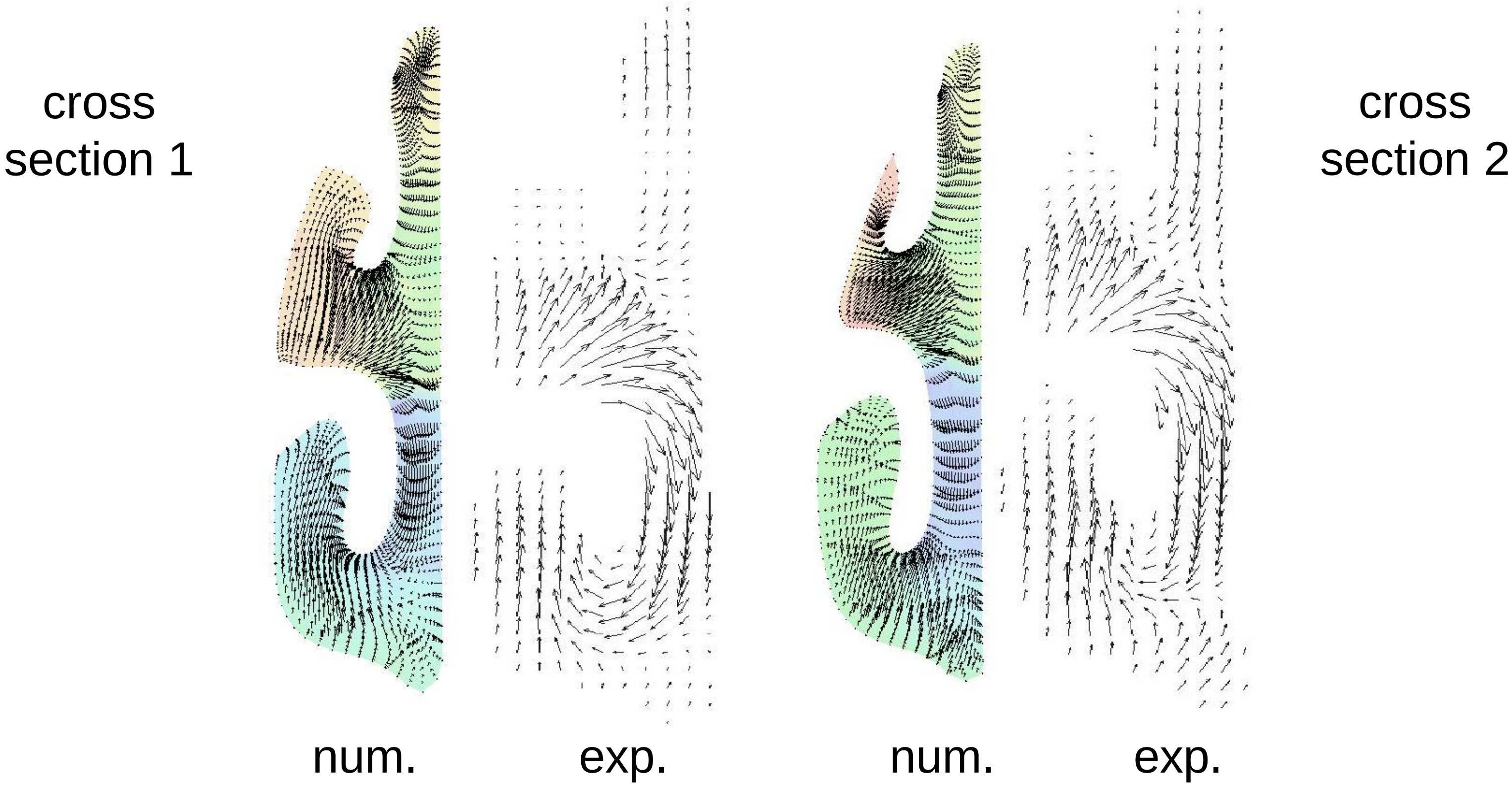


cross section 2

num. exp. num. exp.

1.4.1 Computer assisted surgery of the nose

Results: Comparison of numerics and experiments - Exhalation



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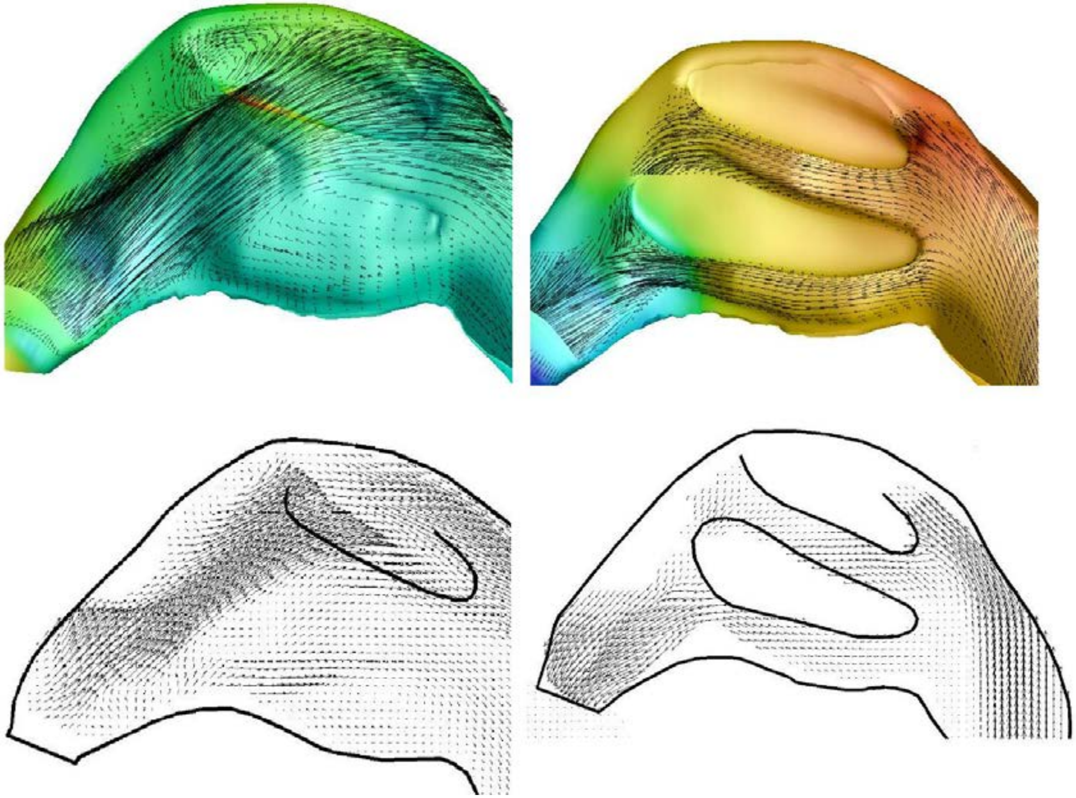
1.4.1 Computer assisted surgery of the nose

Results: Comparison of numerics and experiments

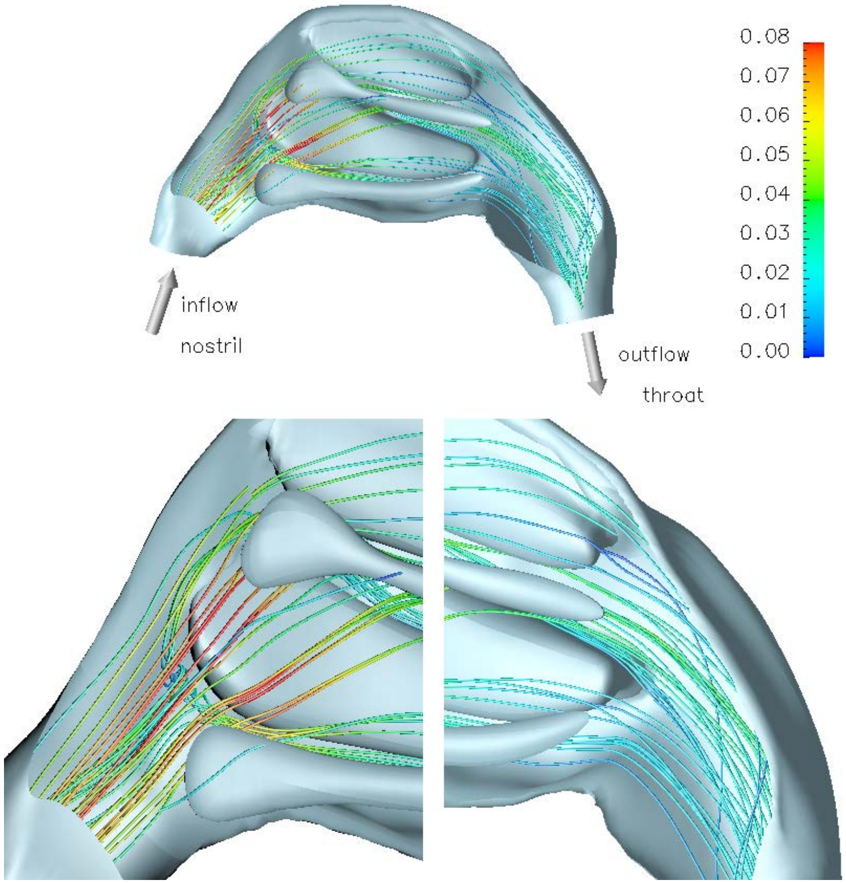
Inhalation | **Exhalation**



1.4.1 Computer assisted surgery of the nose

Results: streamlines – Inhalation

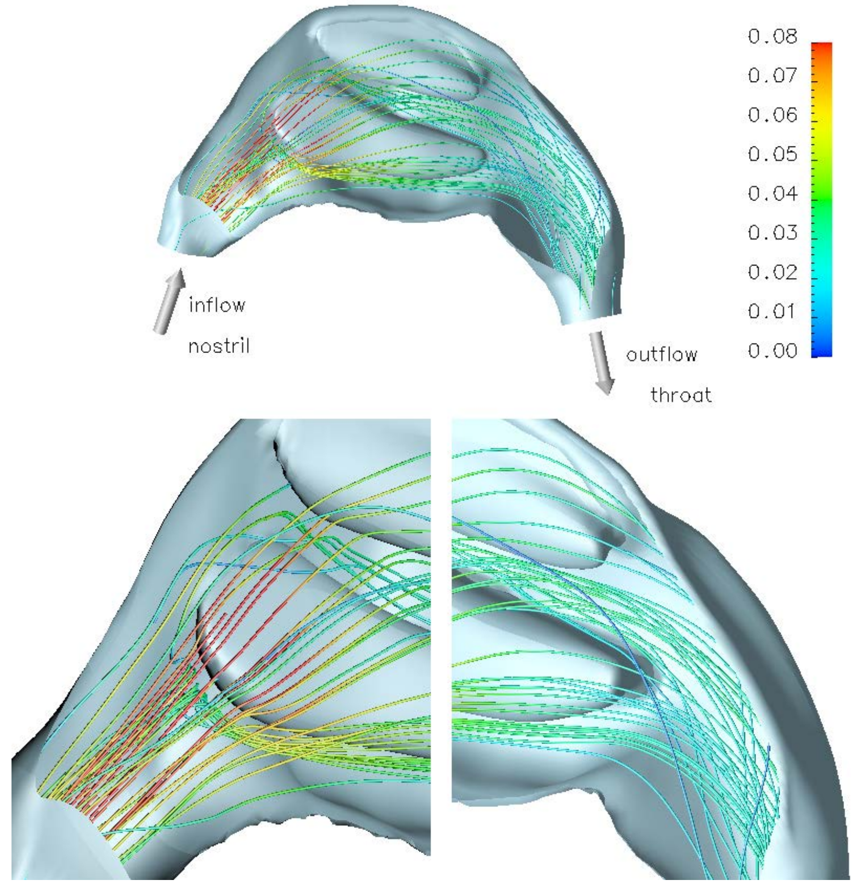
- upper and lower turbinate and spurs



1.4.1 Computer assisted surgery of the nose

Results: streamlines – Inhalation

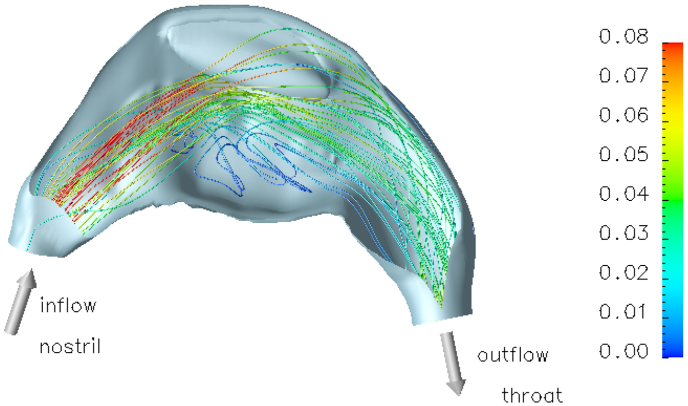
- upper and lower turbinate

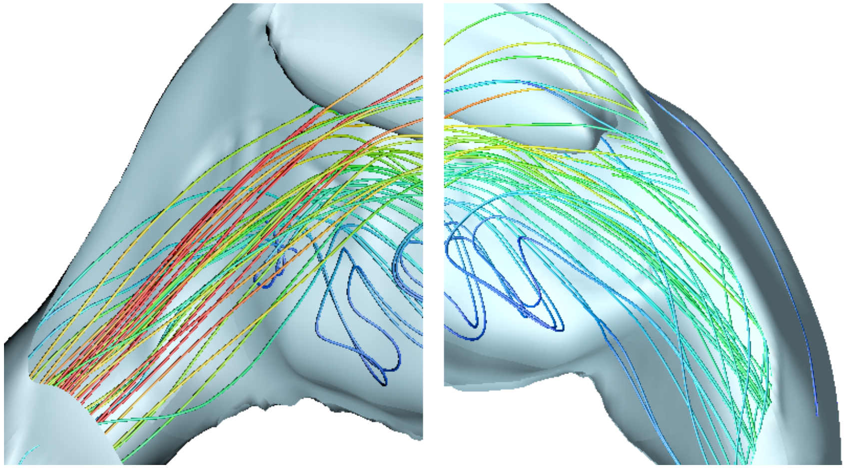


1.4.1 Computer assisted surgery of the nose

Results: streamlines – Inhalation

- upper turbinate

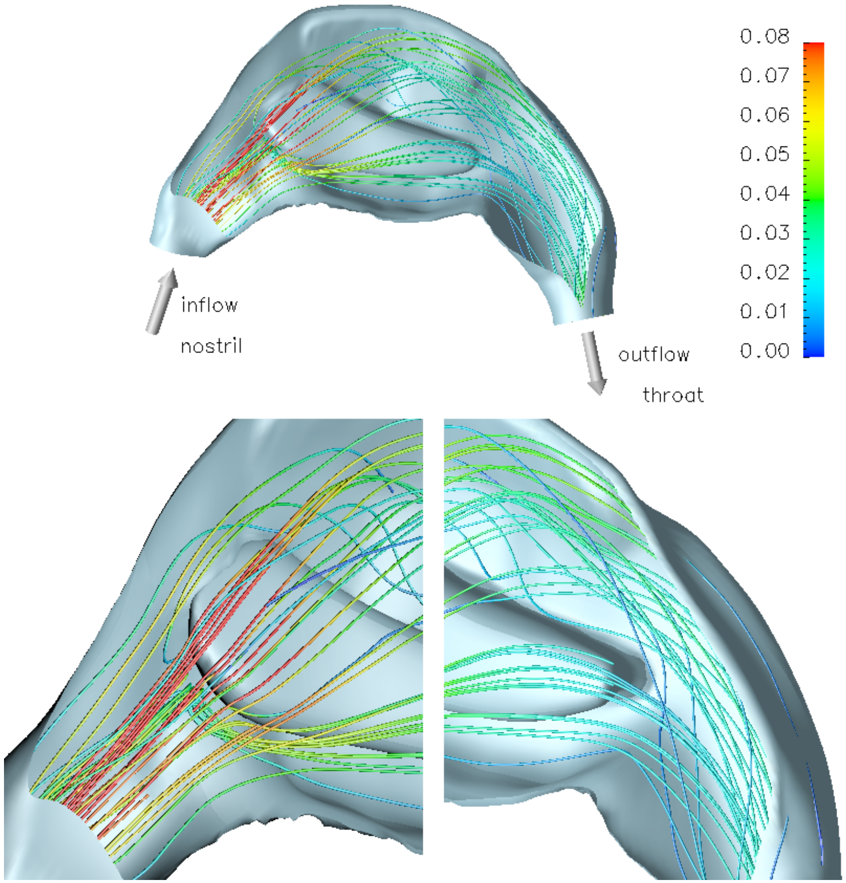




1.4.1 Computer assisted surgery of the nose

Results: streamlines – Inhalation

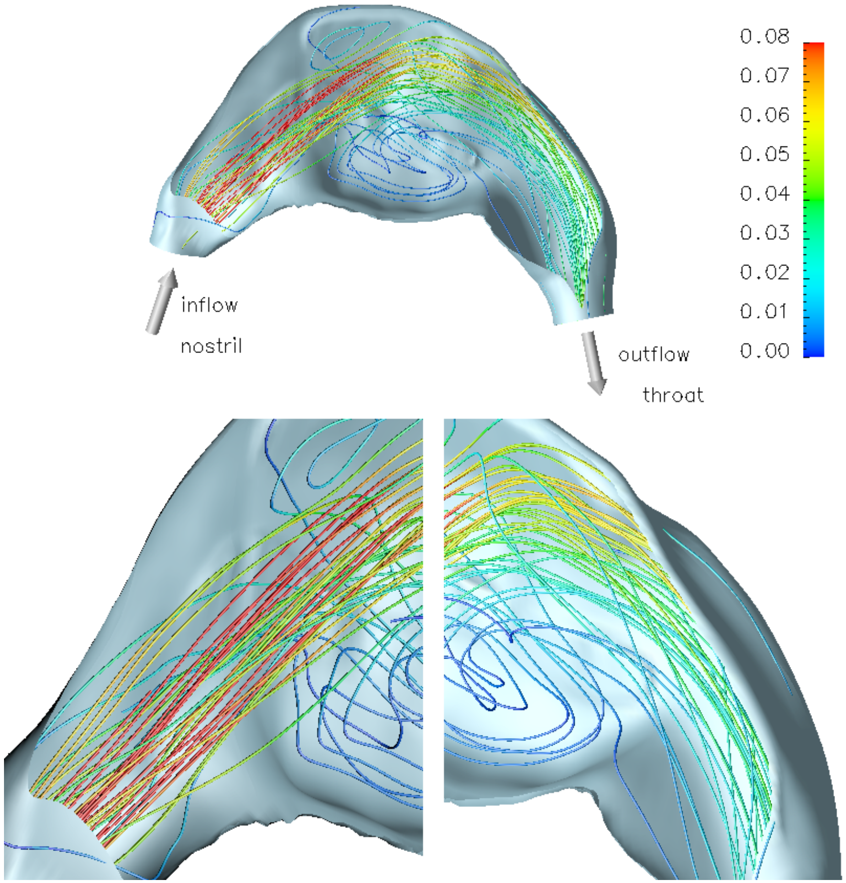
- lower turbinate



1.4.1 Computer assisted surgery of the nose

Results: streamlines – Inhalation

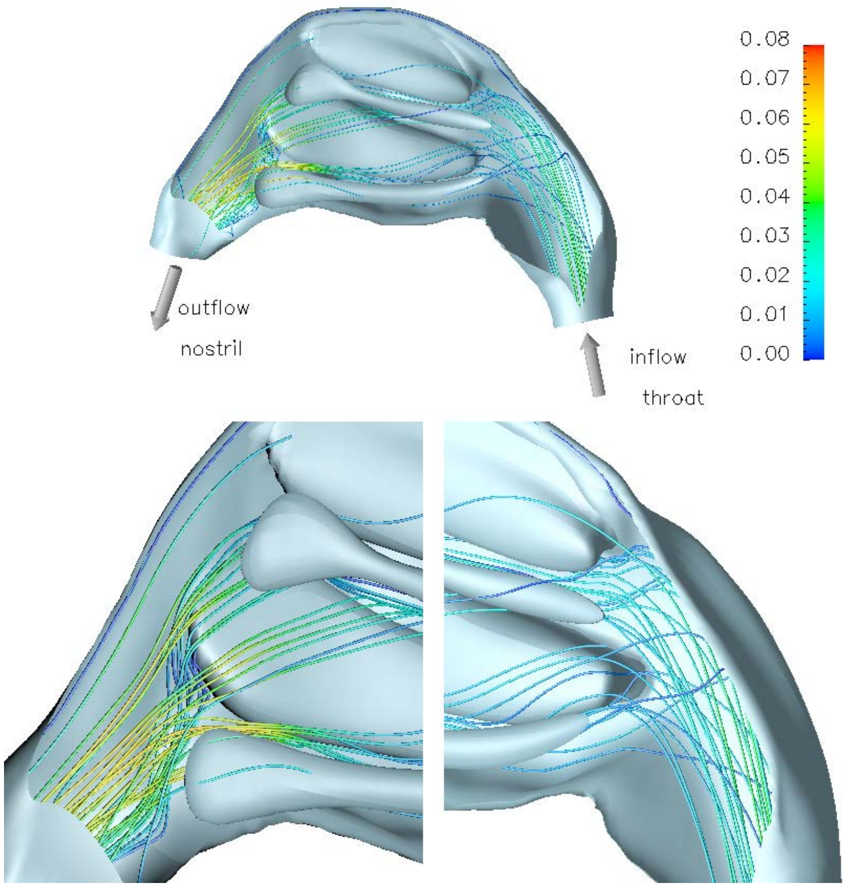
- clean configuration



1.4.1 Computer assisted surgery of the nose

Results: streamlines – Exhalation

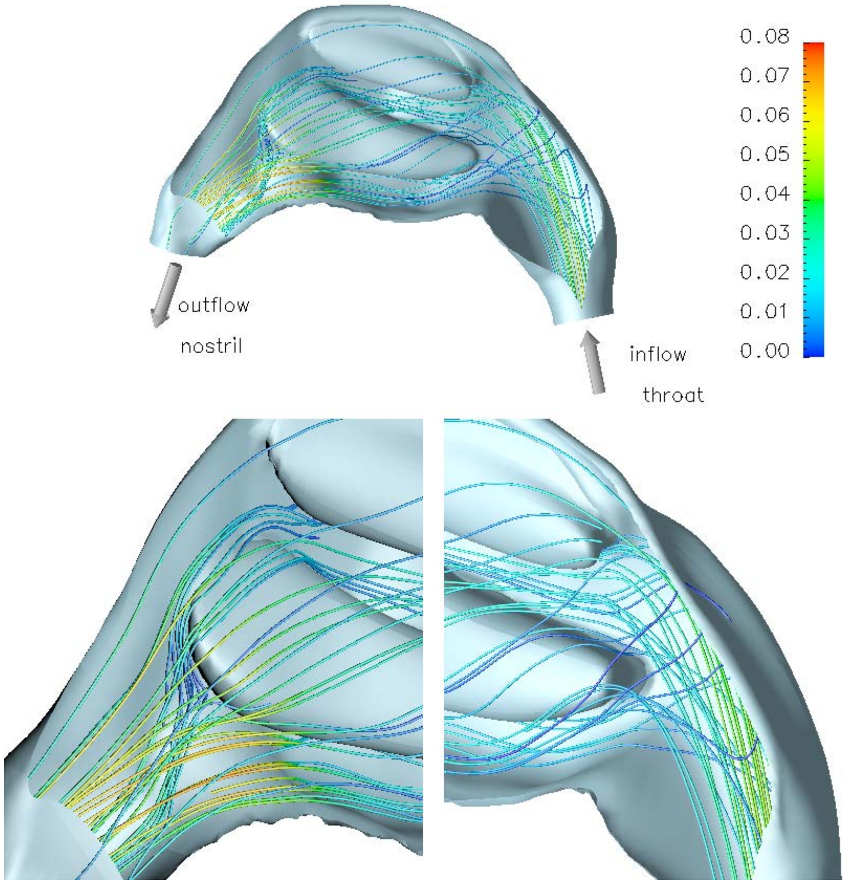
- upper and lower turbinate and spurs



1.4.1 Computer assisted surgery of the nose

Results: streamlines – Exhalation

- upper and lower turbinate

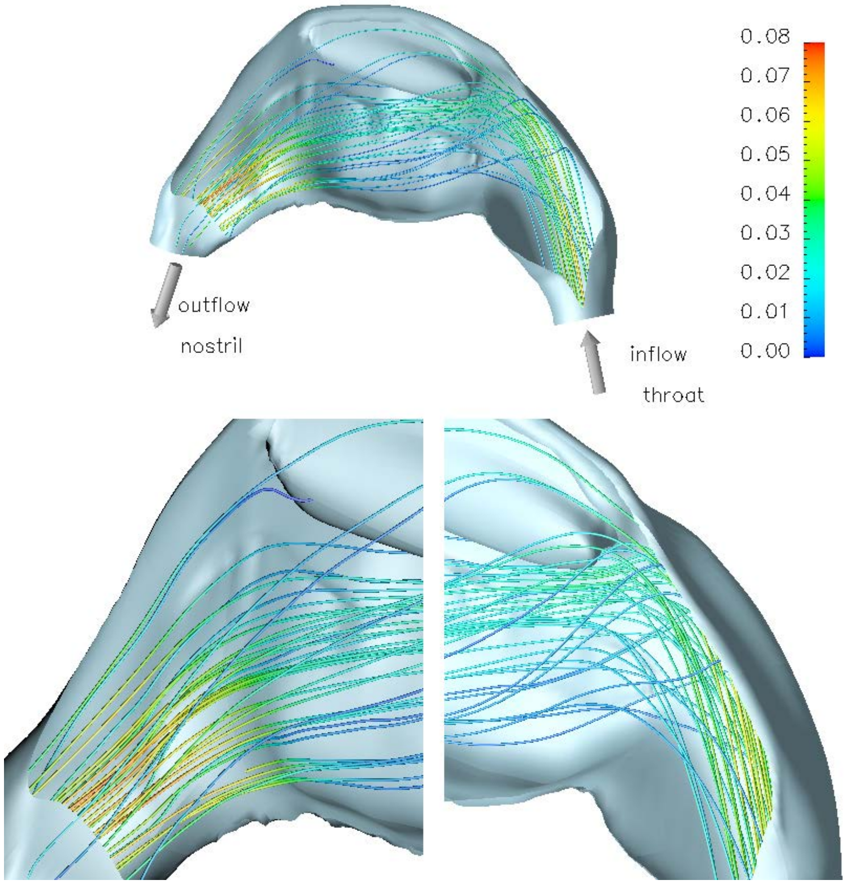


1.4 Examples of application

1.4.1 Computer assisted surgery of the nose

Results: streamlines – Exhalation

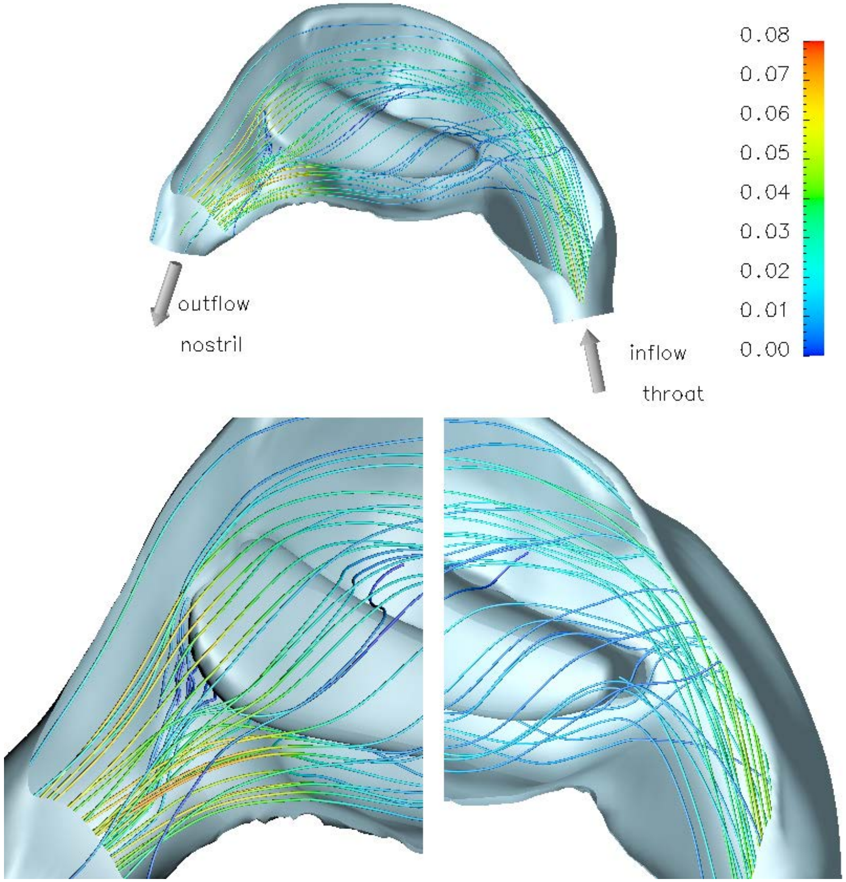
- upper turbinate



1.4.1 Computer assisted surgery of the nose

Results: streamlines – Exhalation

- lower turbinate



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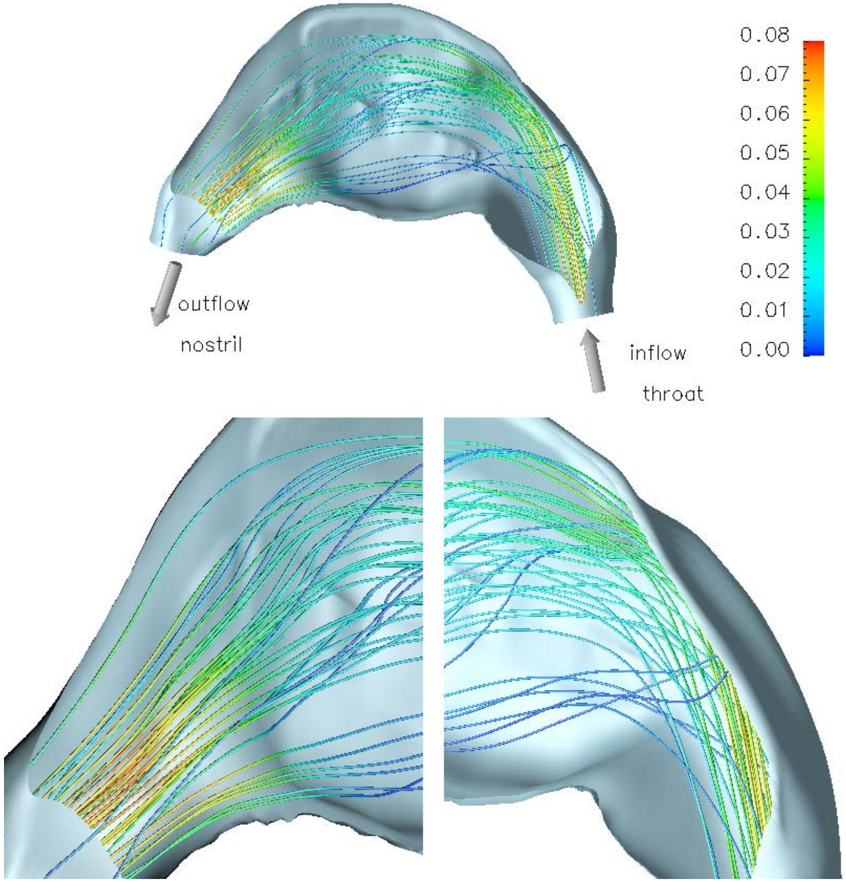
1.4.1 Computer assisted surgery of the nose

Results: streamlines – Exhalation

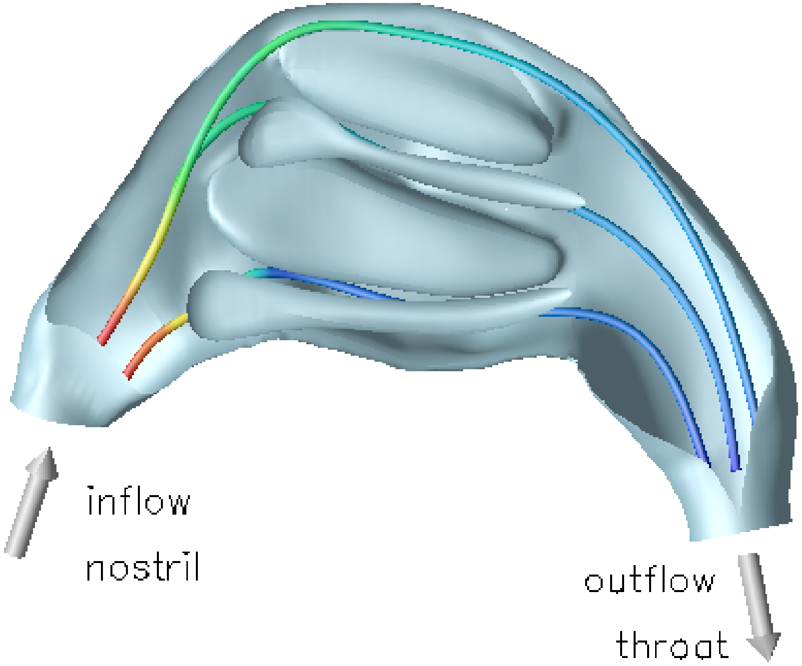
- clean configuration

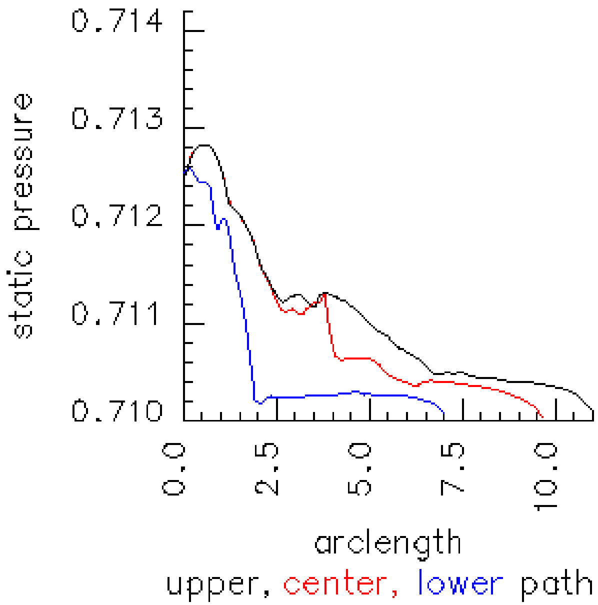


1.4.1 Computer assisted surgery of the nose

Results: pressure distribution – Inhalation

- upper and lower turbinate and spurs

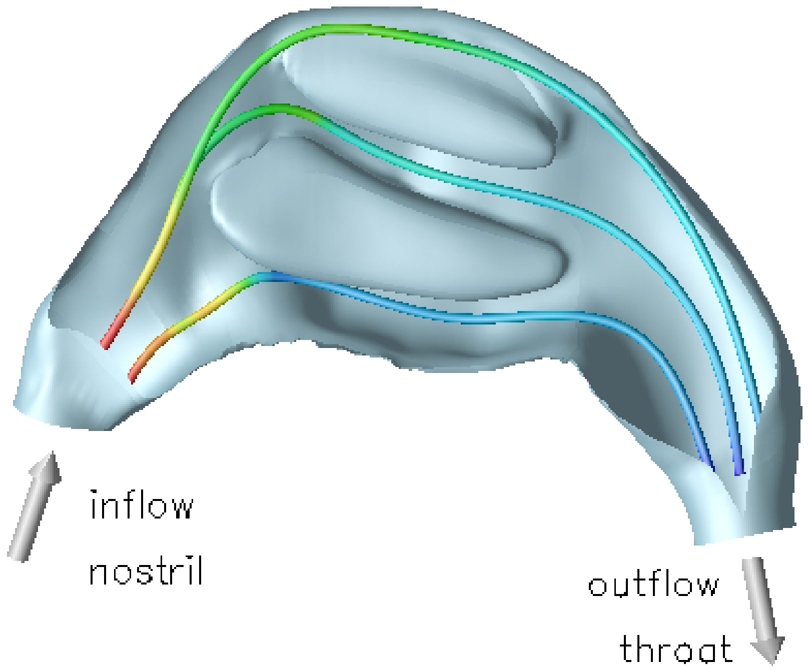


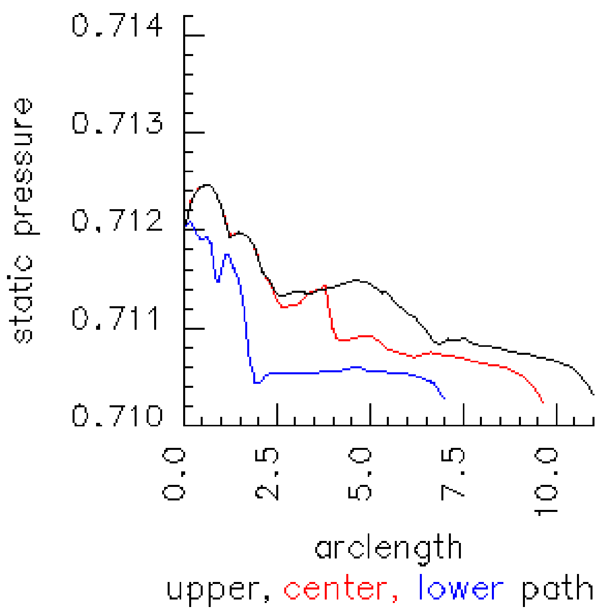


1.4.1 Computer assisted surgery of the nose

Results: pressure distribution – Inhalation

- upper and lower turbinate

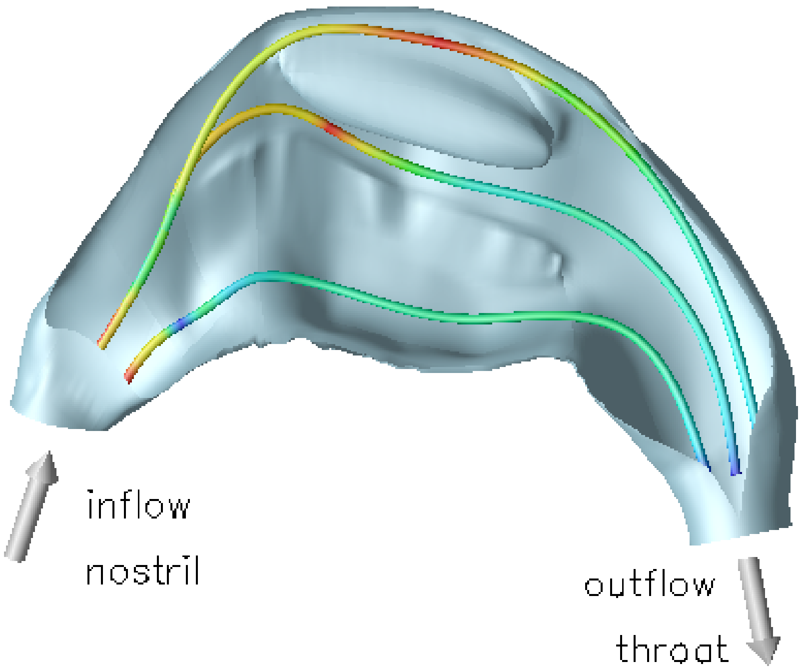


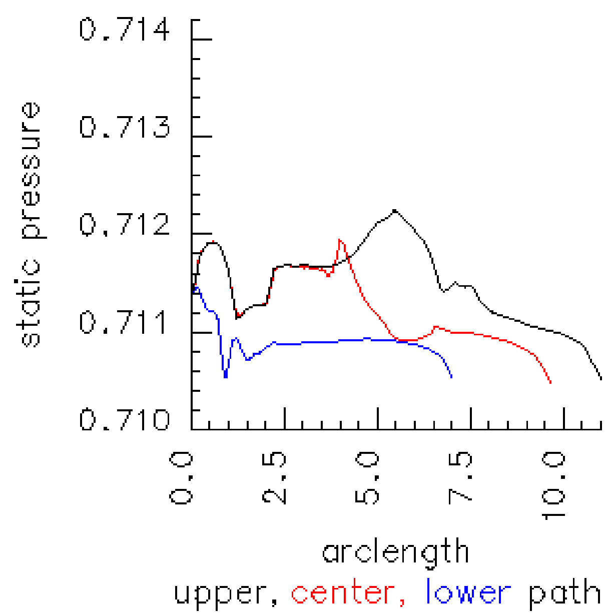


1.4.1 Computer assisted surgery of the nose

Results: pressure distribution – Inhalation

- upper turbinate

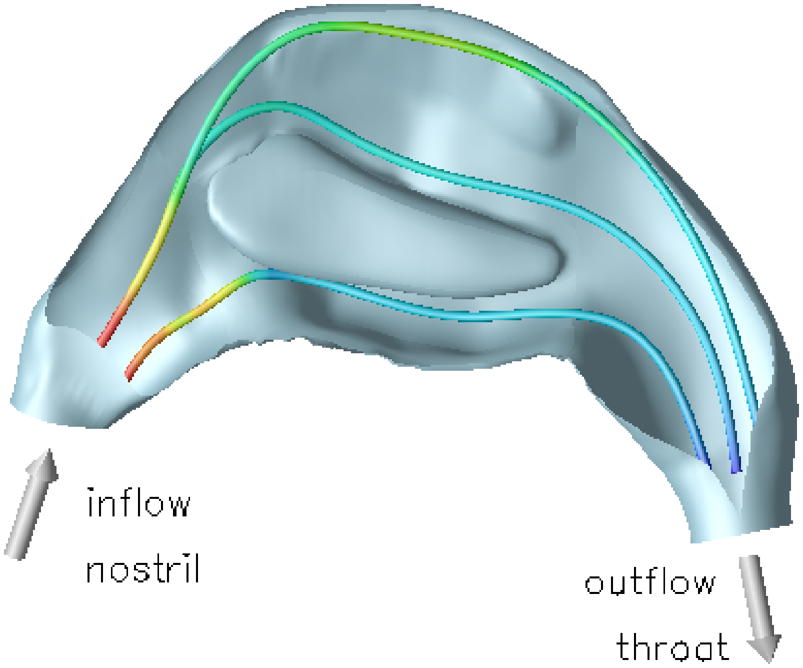


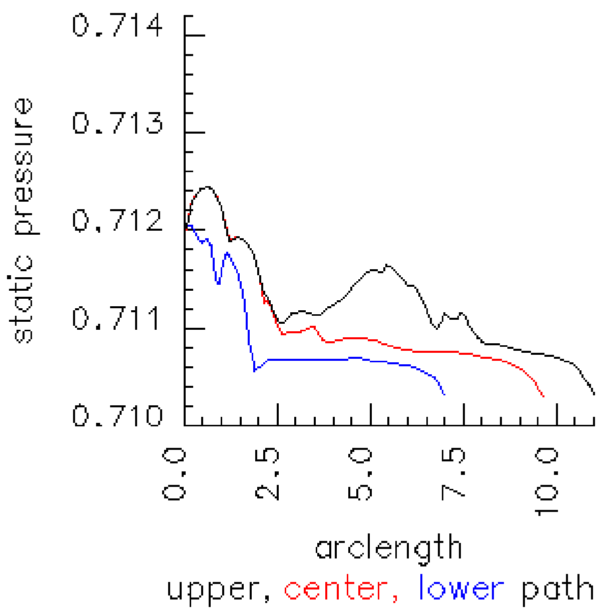


1.4.1 Computer assisted surgery of the nose

Results: pressure distribution – Inhalation

- lower turbinate

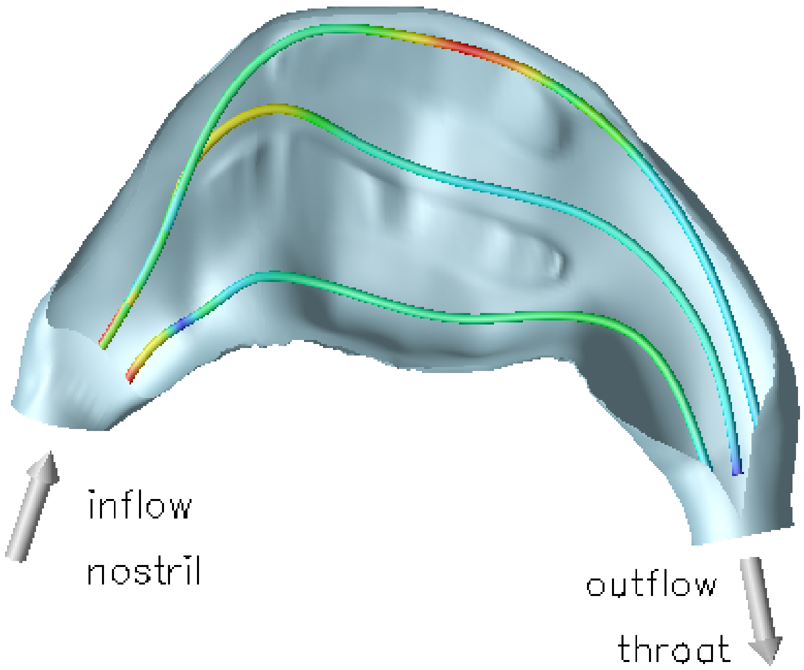


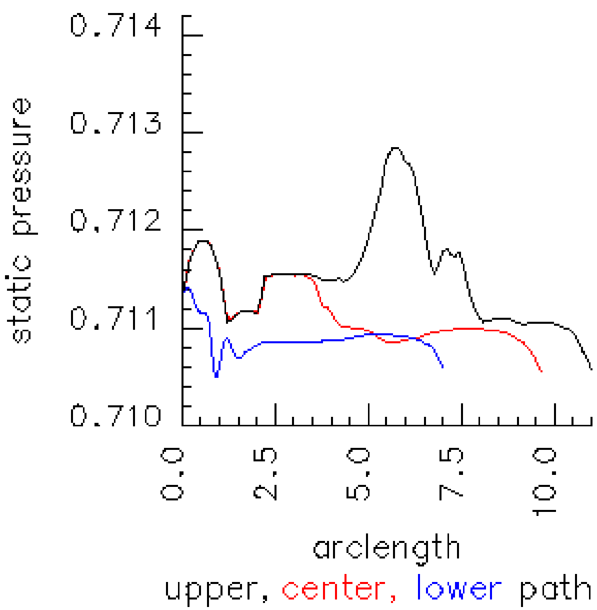


1.4.1 Computer assisted surgery of the nose

Results: pressure distribution – Inhalation

- clean configuration

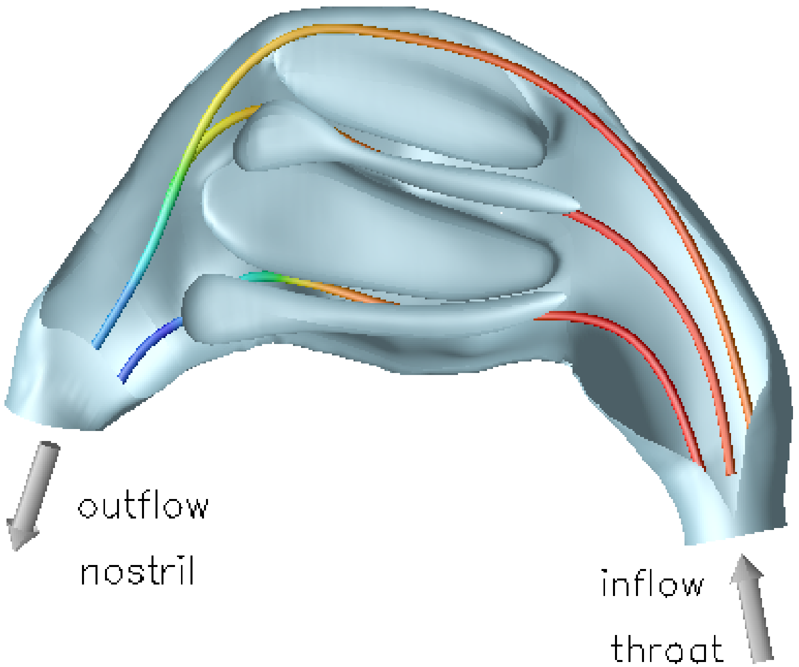


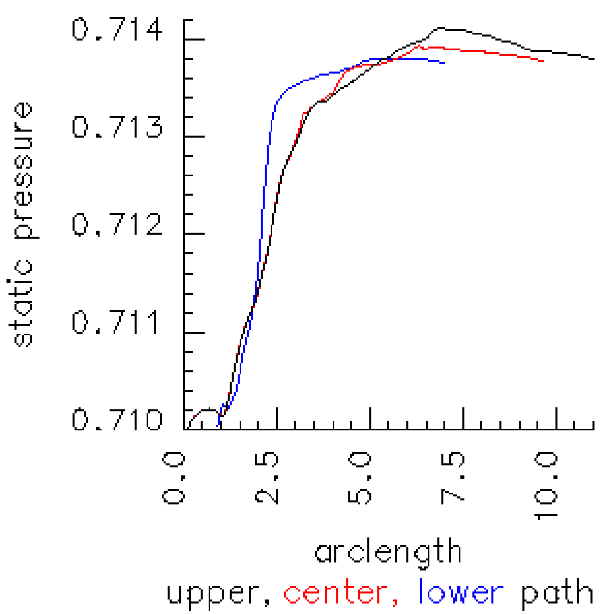


1.4.1 Computer assisted surgery of the nose

Results: pressure distribution – Exhalation

- upper and lower turbinate and spurs





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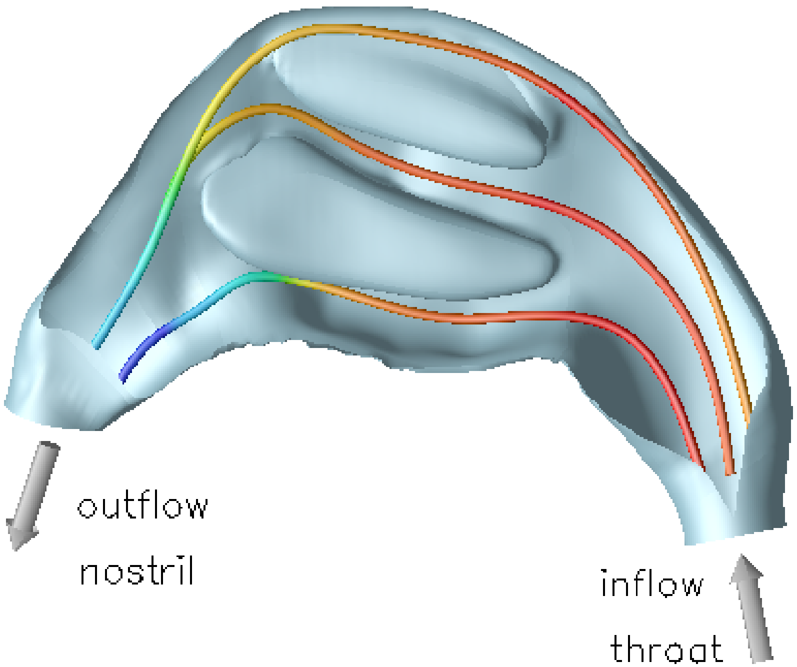
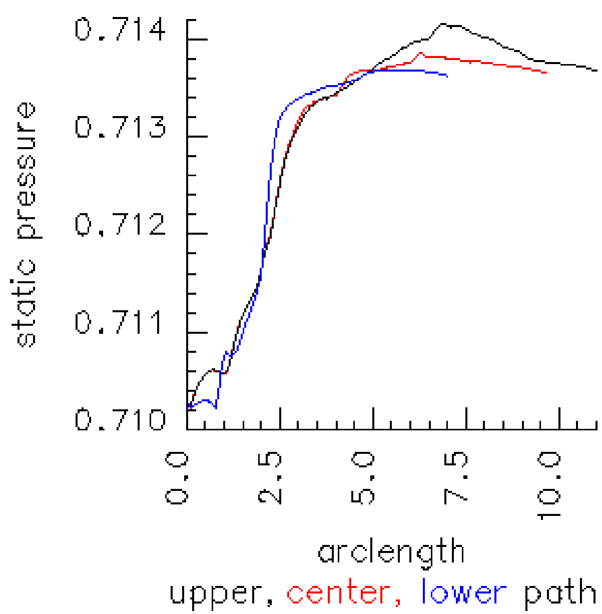
1.4 Examples of application

1.4.1 Computer assisted surgery of the nose

Results: pressure distribution – Exhalation

- upper and lower turbinate





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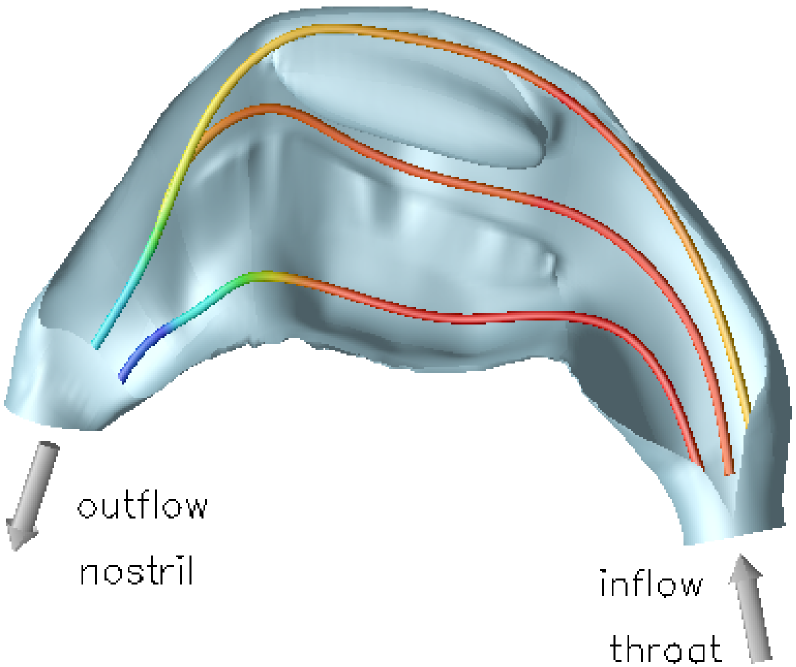
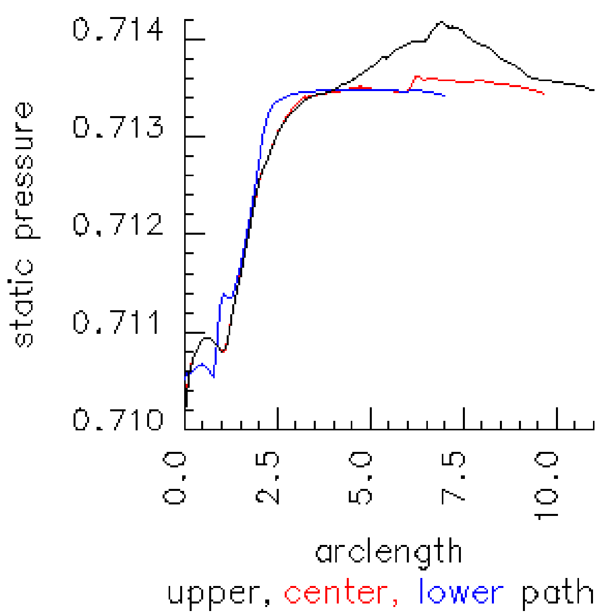
1.4.1 Computer assisted surgery of the nose

Results: pressure distribution – Exhalation

- upper turbinate

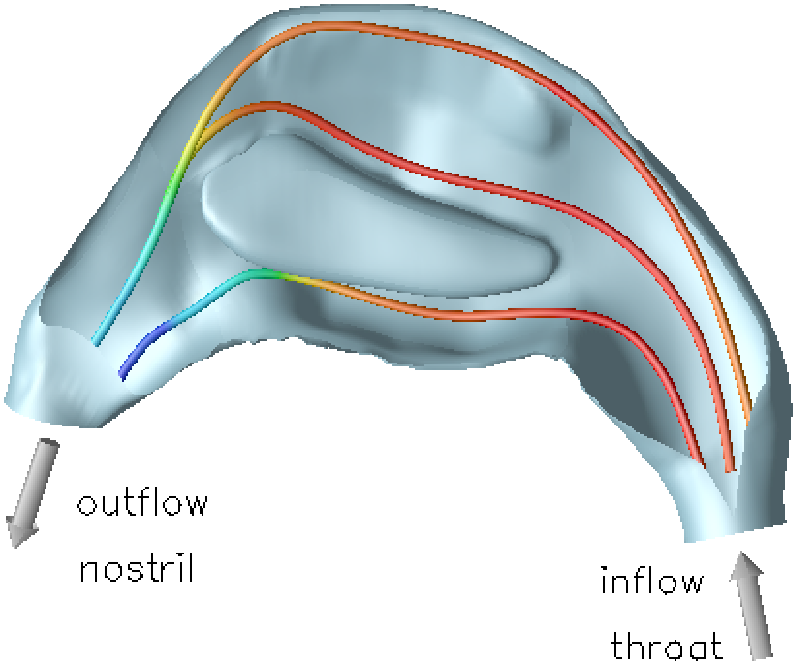


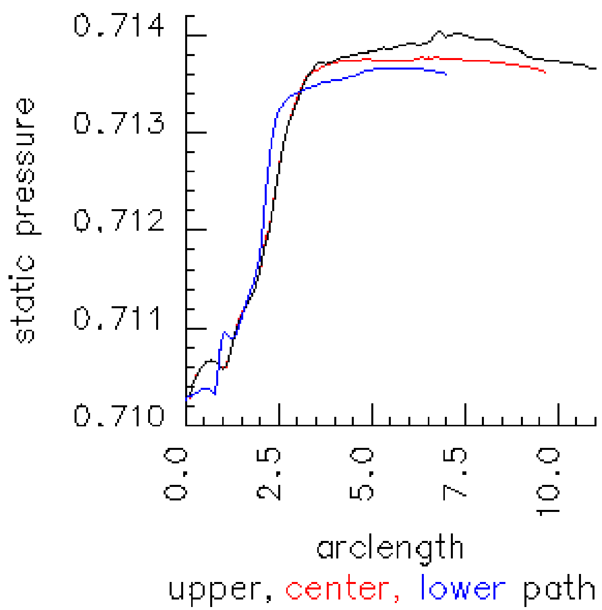


1.4.1 Computer assisted surgery of the nose

Results: pressure distribution – Exhalation

- lower turbinate

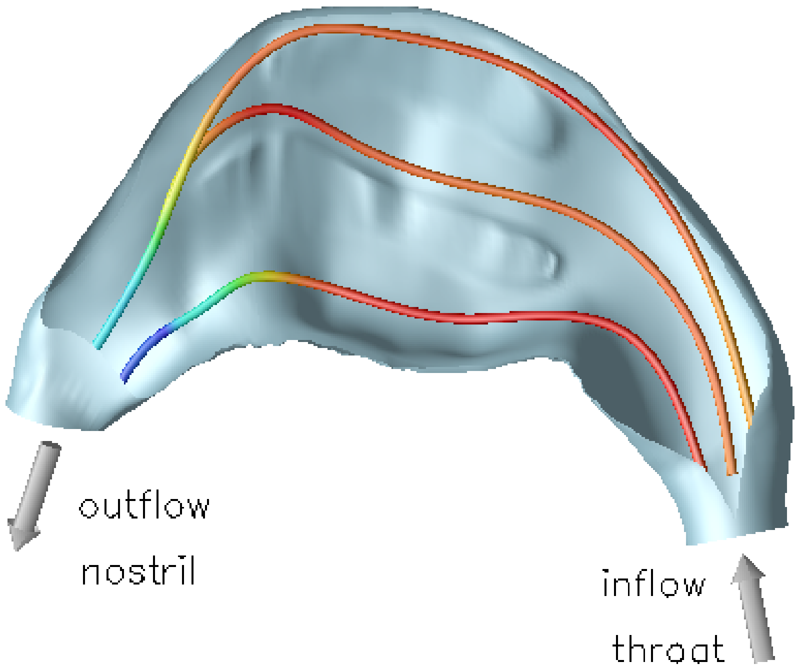


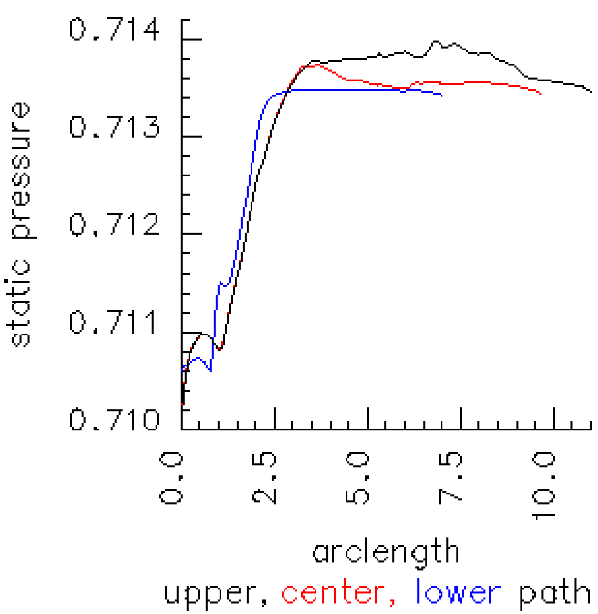


1.4.1 Computer assisted surgery of the nose

Results: pressure distribution – Exhalation

- clean configuration





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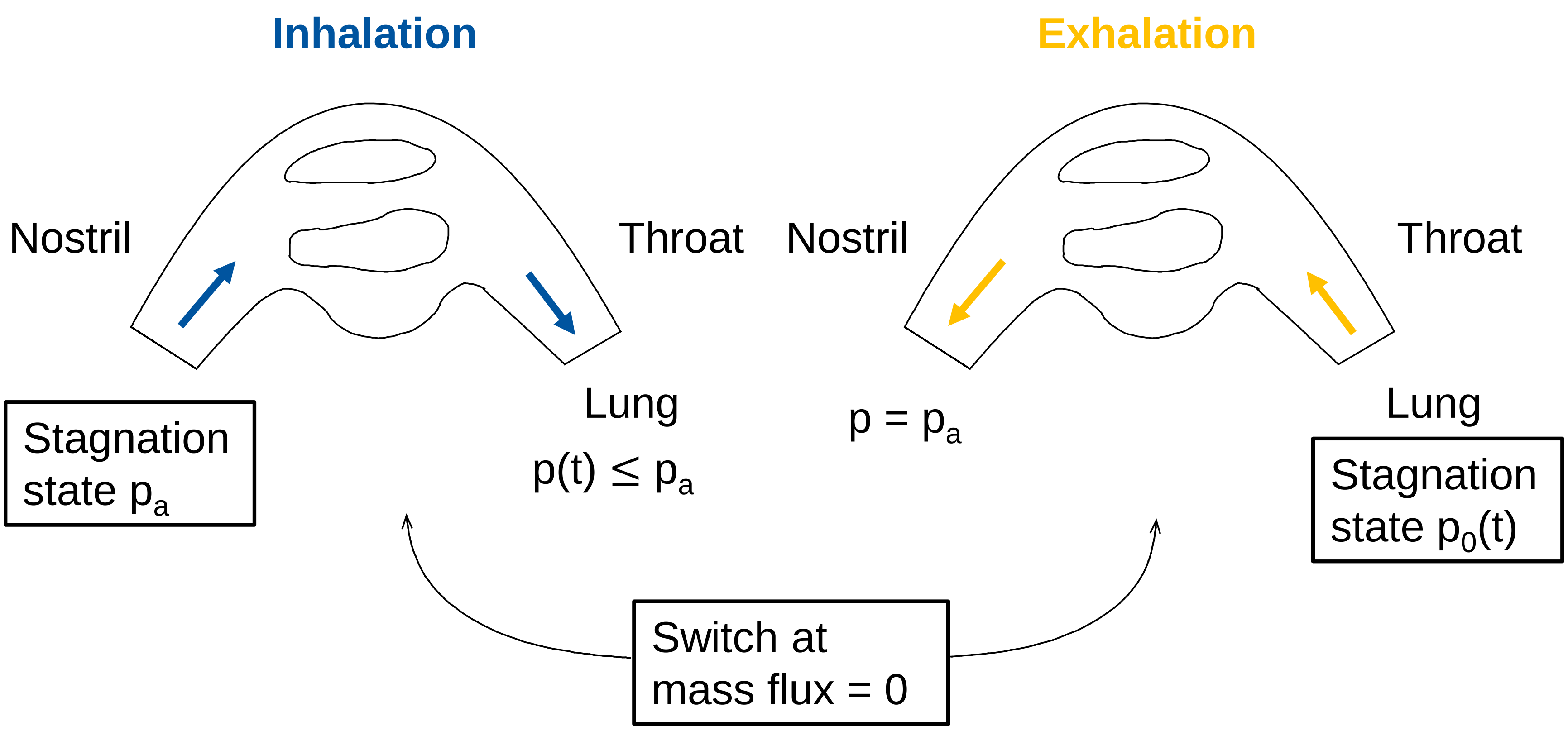
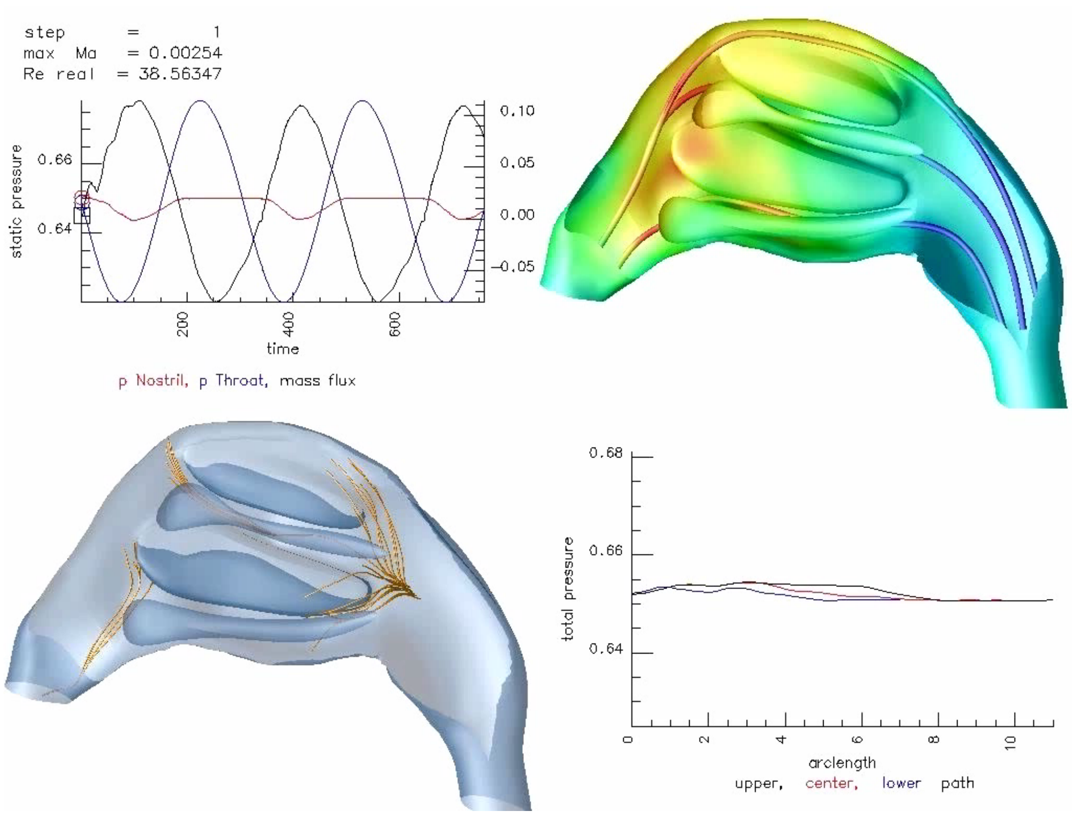
1.4.1 Computer assisted surgery of the nose

Scheme for human respiration cycle



1.4.1 Computer assisted surgery of the nose

Results: Inhalation / Exhalation process

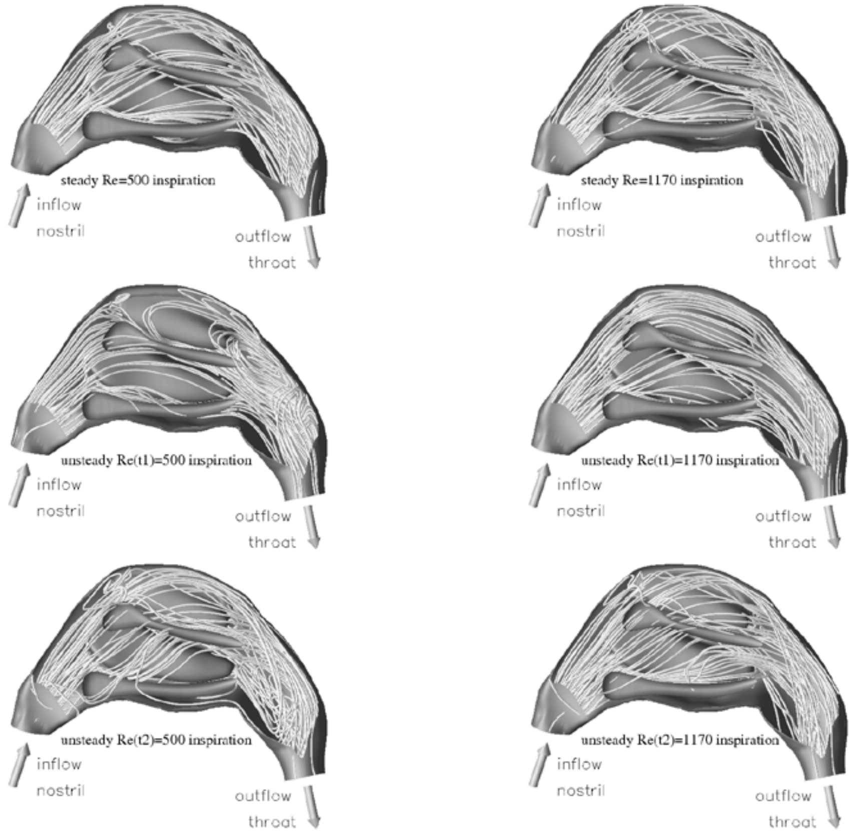


1.4 Examples of application

1.4.1 Computer assisted surgery of the nose

Results: streamlines at Inhalation

Re=500



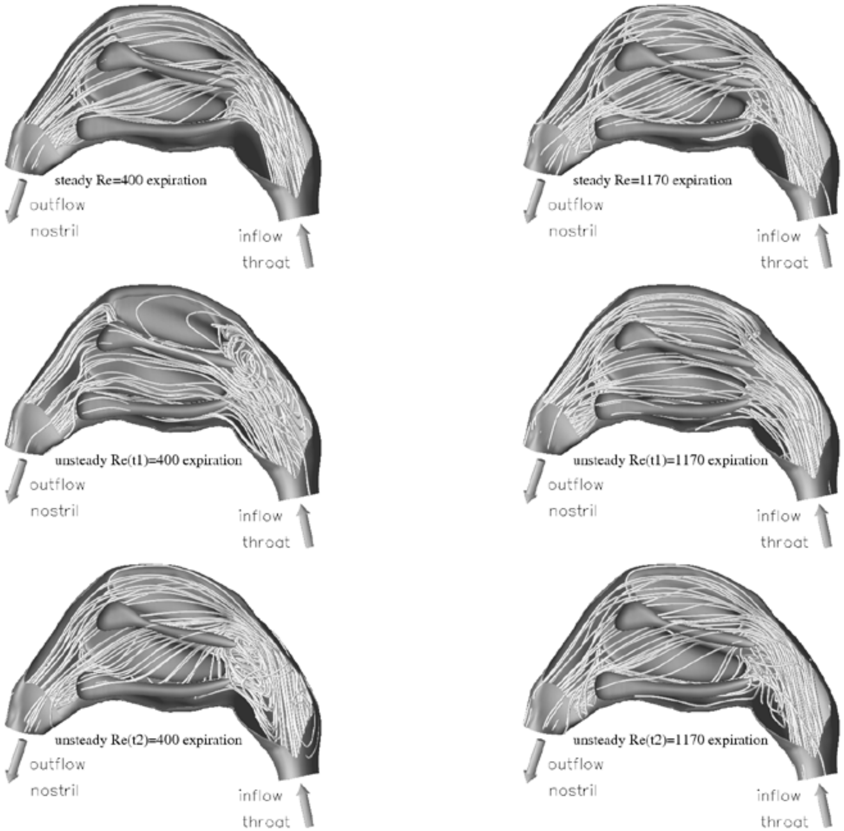
Re=1170

1.4 Examples of application

1.4.1 Computer assisted surgery of the nose

Results: streamlines at Exhalation

Re=400



Re=1170

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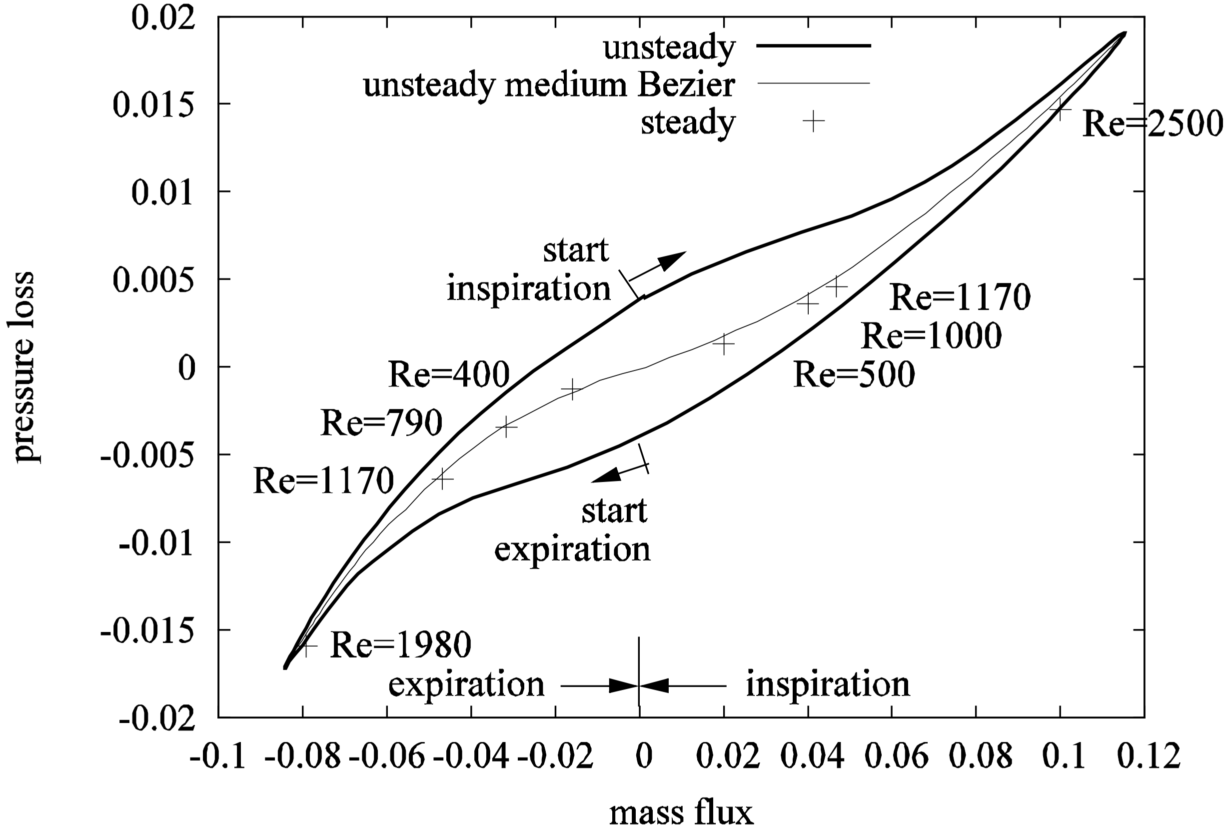
1.4.1 Computer assisted surgery of the nose

pressure loss vs. mass flux



Lecture contents

1. Introduction	Exercise
1.1 Transportation processes in the human body 1.1.1 Exchange of respiratory gases 1.1.2 Blood circulation 1.1.3 Other transportation processes	
1.2 Transportation processes in medical devices	
1.3 Tasks of fluid mechanics in medicine	
1.4 Examples of application 1.4.1 Computer assisted surgery of the nose 1.4.2 Examination of the airway flow 1.4.3 Investigation of an artificial heart valve 1.4.4 Silent flight of the owl	

1.4.2 Examination of the airway flow

Characteristics of the airway flow

- unsteady, pulsating flow
- complex geometry
- multiple bifurcations

Fig.1.13: Example of the human airway network in the respiratory system

1.4.2 Examination of the airway flow

Trap and release mechanism

Mochizuki (2003)

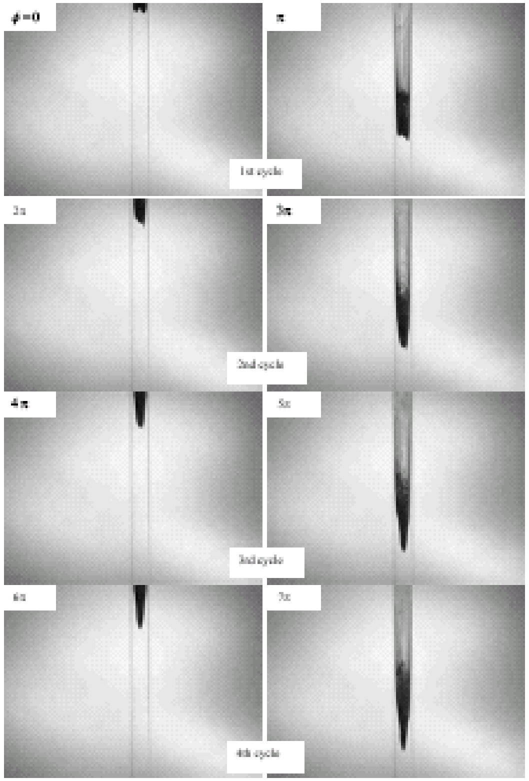


Fig. 5. Time wise variation of fluid flow inside straight tube between 1st and 4th cycles

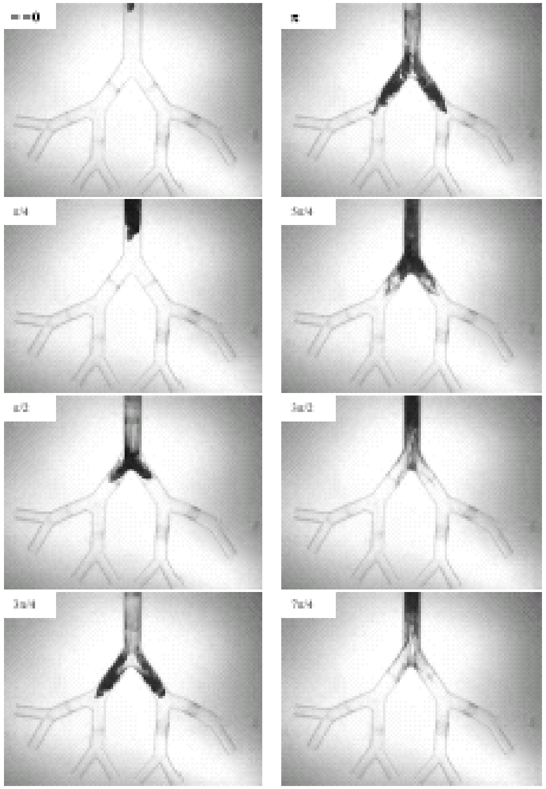


Fig. 8a. Time wise variation of fluid flow inside regular dichotomy during 1st cycle ($\phi = 0 \sim 7\pi/4$)

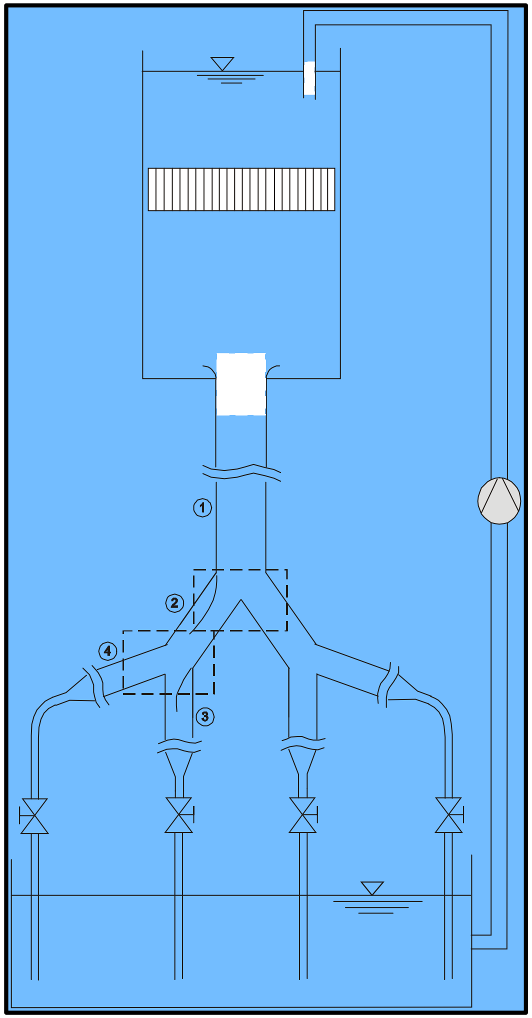
Multiple bifurcation

1.4.2 Examination of the airway flow

Flow oscillations in a multiple bifurcation flow

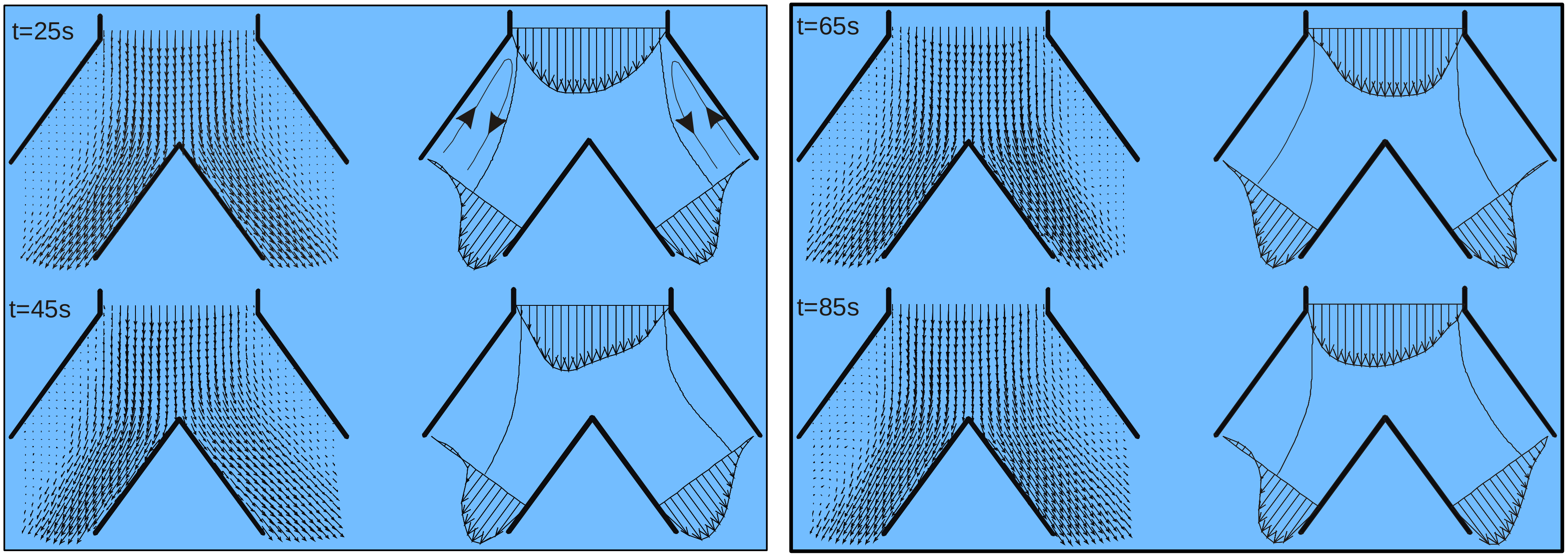
Analysis of mass flow fluctuations in multiple bifurcations

- model: 2D bifurcation, 2nd generation (Weibel's data)
- fluid: water glycerin
- flow parameter: steady inflow, Re_p=700
- PIV recordings: simultaneous, long-term video recordings at 4 locations



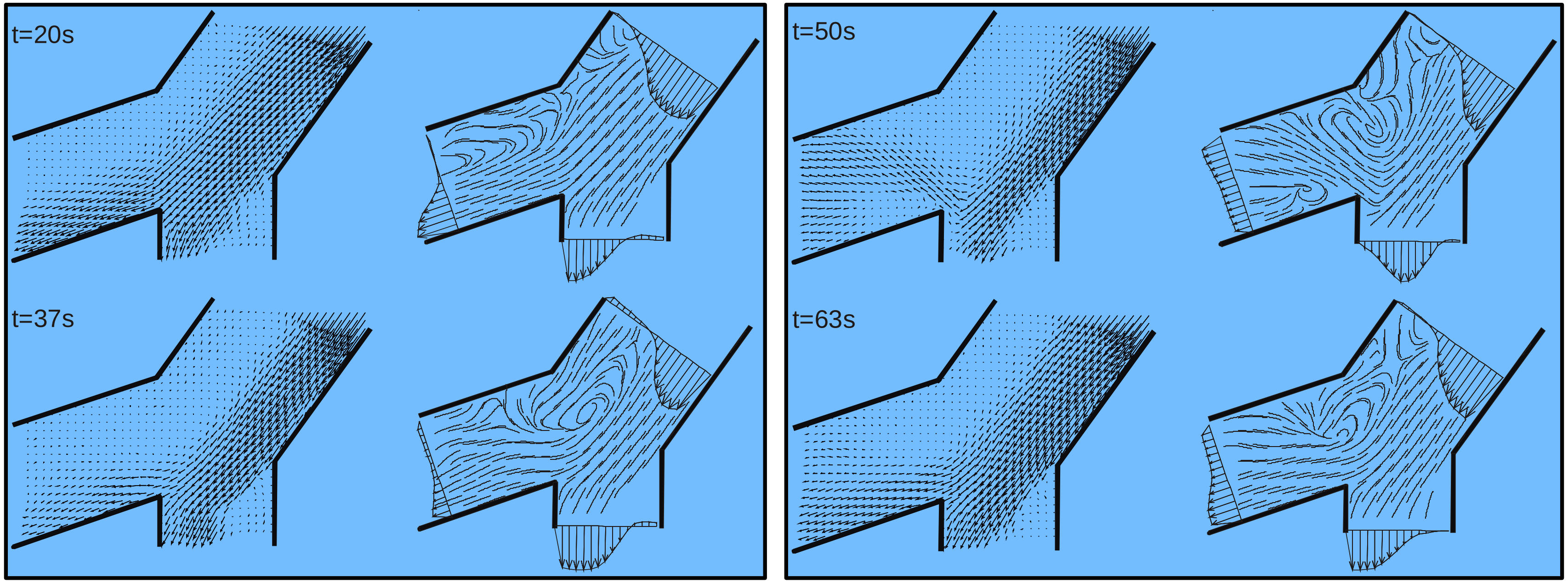
1.4.2 Examination of the airway flow

Results: oscillations in the 1st generation



1.4.2 Examination of the airway flow

Results: oscillations in the 2nd generation



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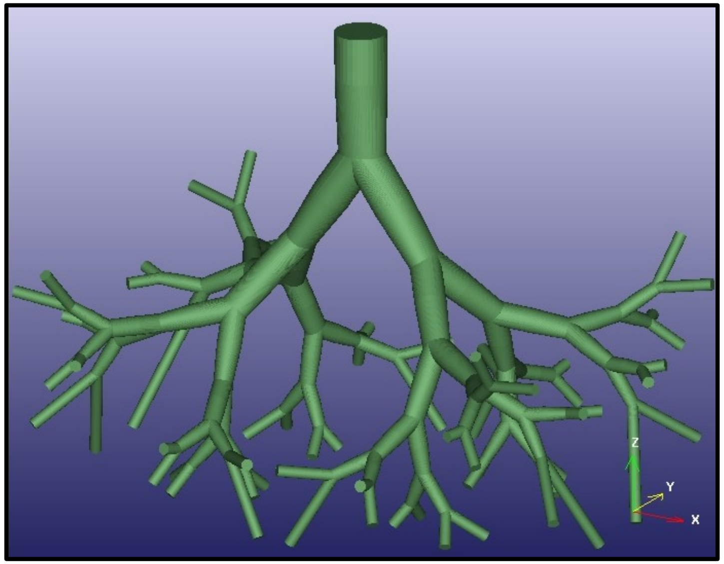
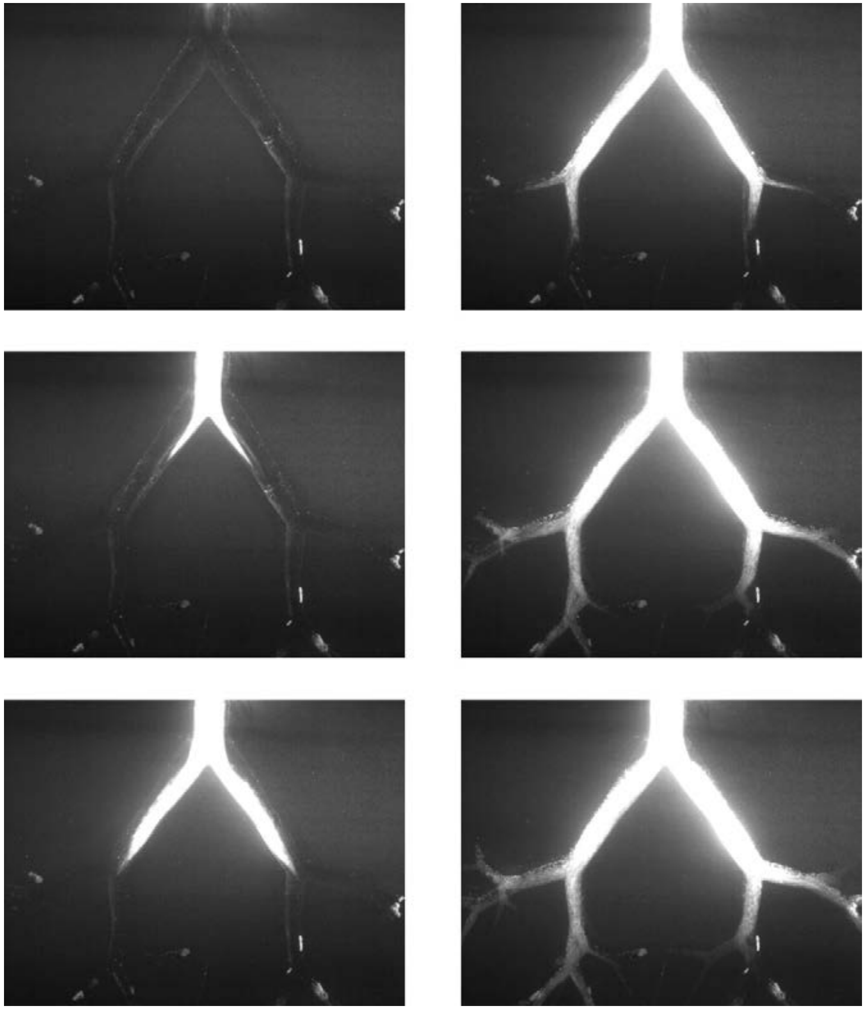
1.4.2 Examination of the airway flow

Inhalation – flow visualization

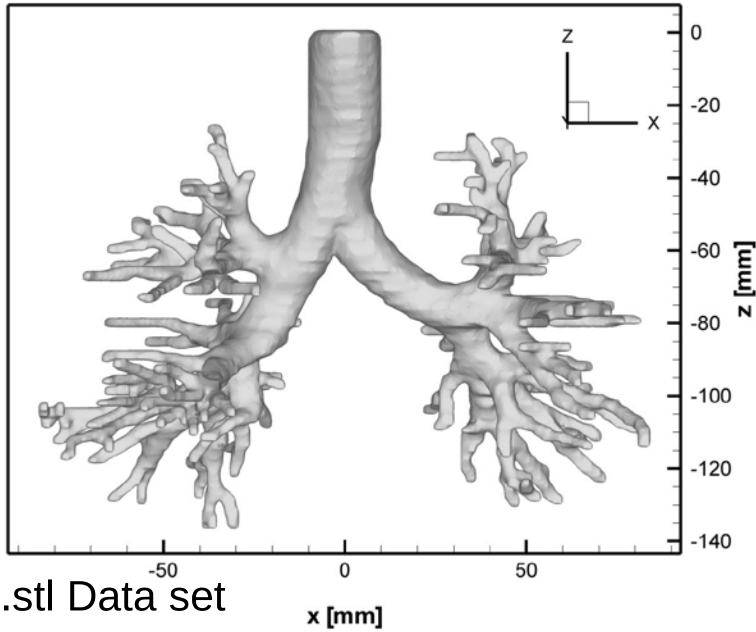




- generic lung model
- hydrogen bubbles

1.4.2 Examination of the airway flow

Reconstruction of the geometry

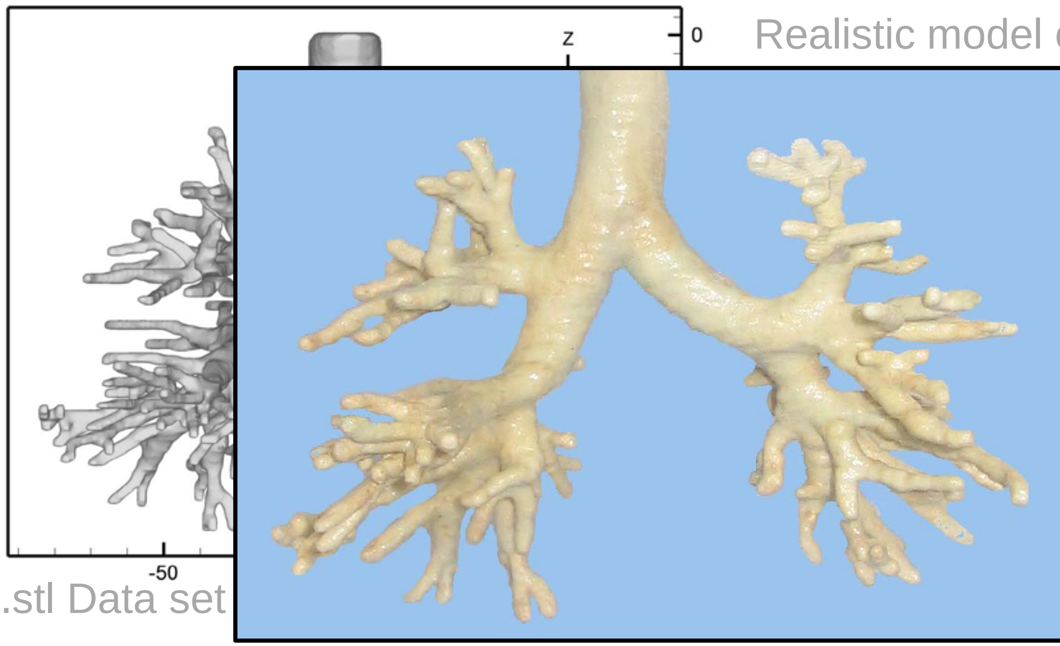


.stl Data set

Realistic model of human lung down to the 6th generation

1.4.2 Examination of the airway flow

Reconstruction of the geometry



.stl Data set

Realistic model of human lung down to the 6th generation

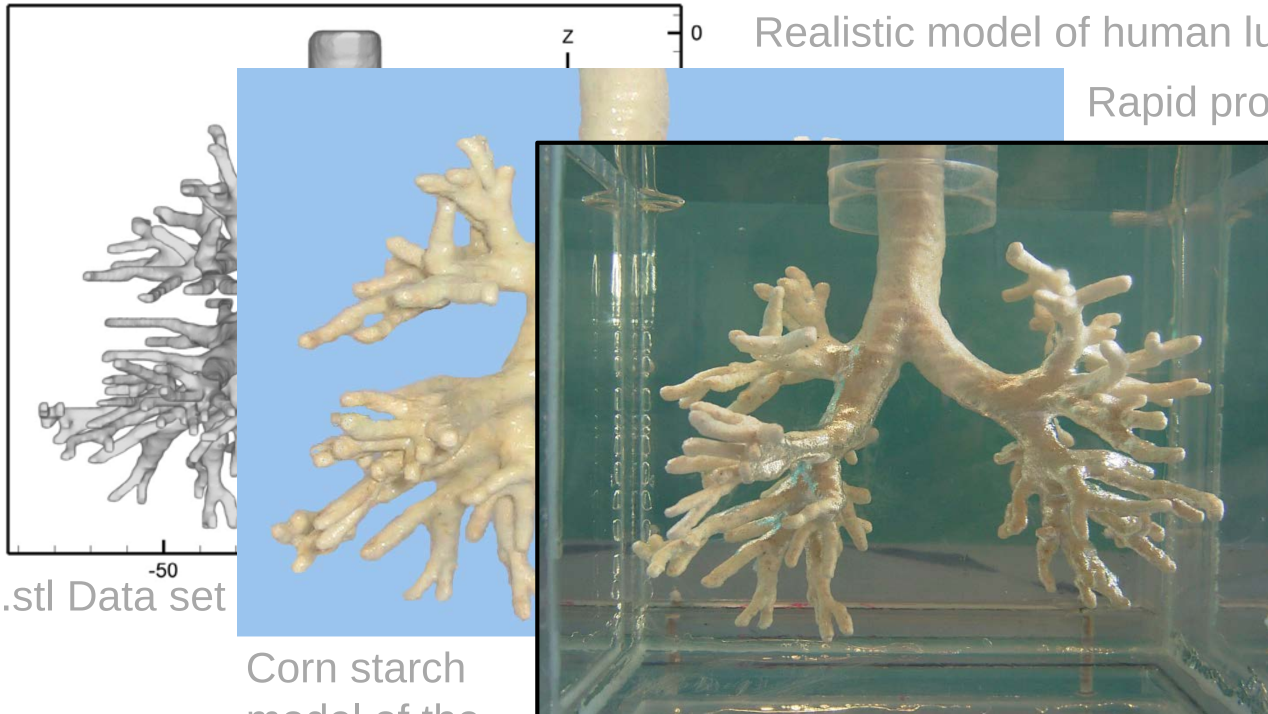
Rapid prototyping

Corn starch model of the upper airways

1.4.2 Examination of the airway flow

Reconstruction of the geometry

Realistic model of human lung down to the 6th generation



.stl Data set

Rapid prototyping

Corn starch model of the upper airways

Moulded silicone block

Silicone block with immersed corn starch model

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1.4.2 Examination of the airway flow

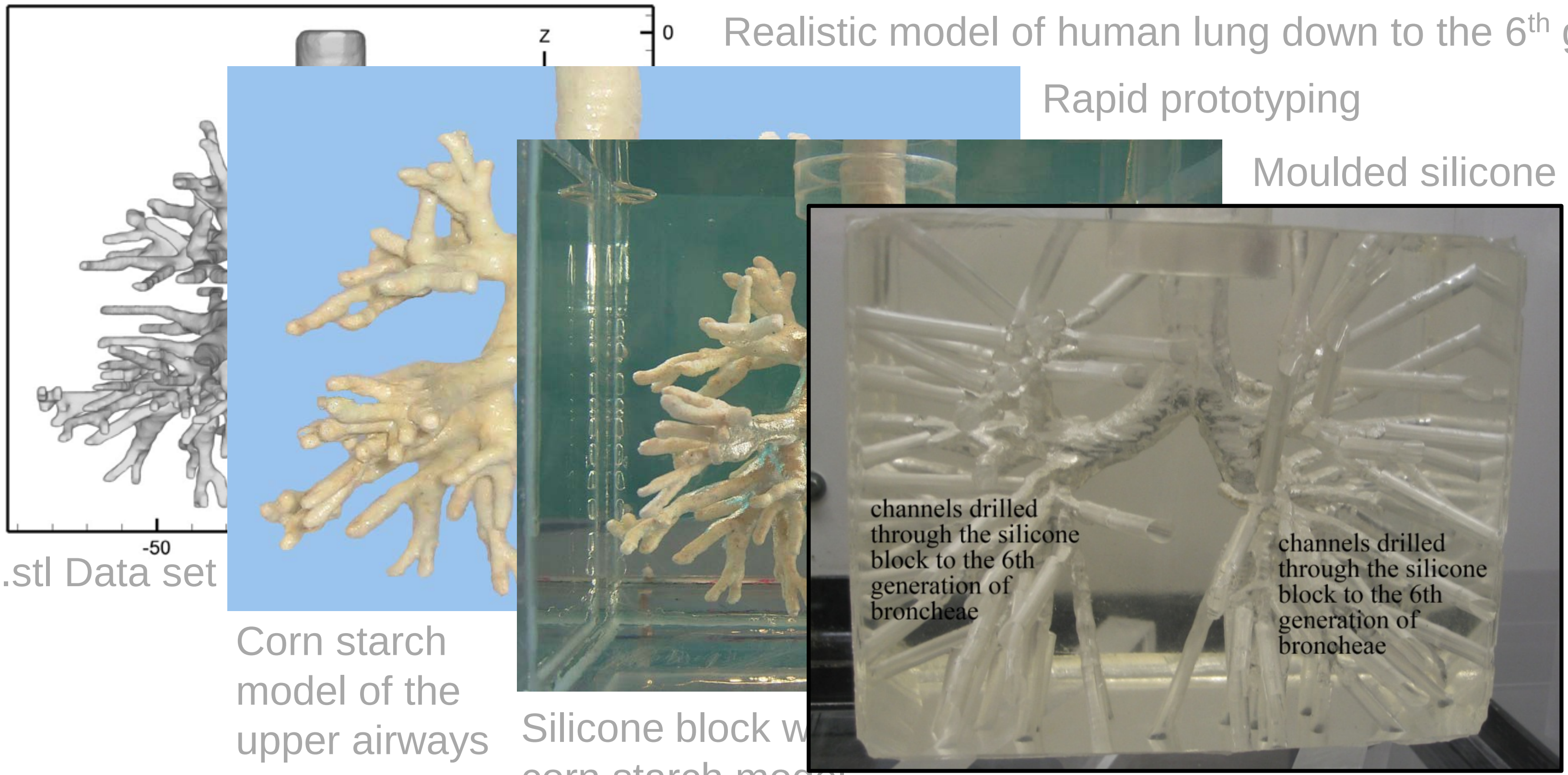
Reconstruction of the geometry

Realistic model of human lung down to the 6th generation

Rapid prototyping

Moulded silicone block

Washout of the starch



.stl Data set

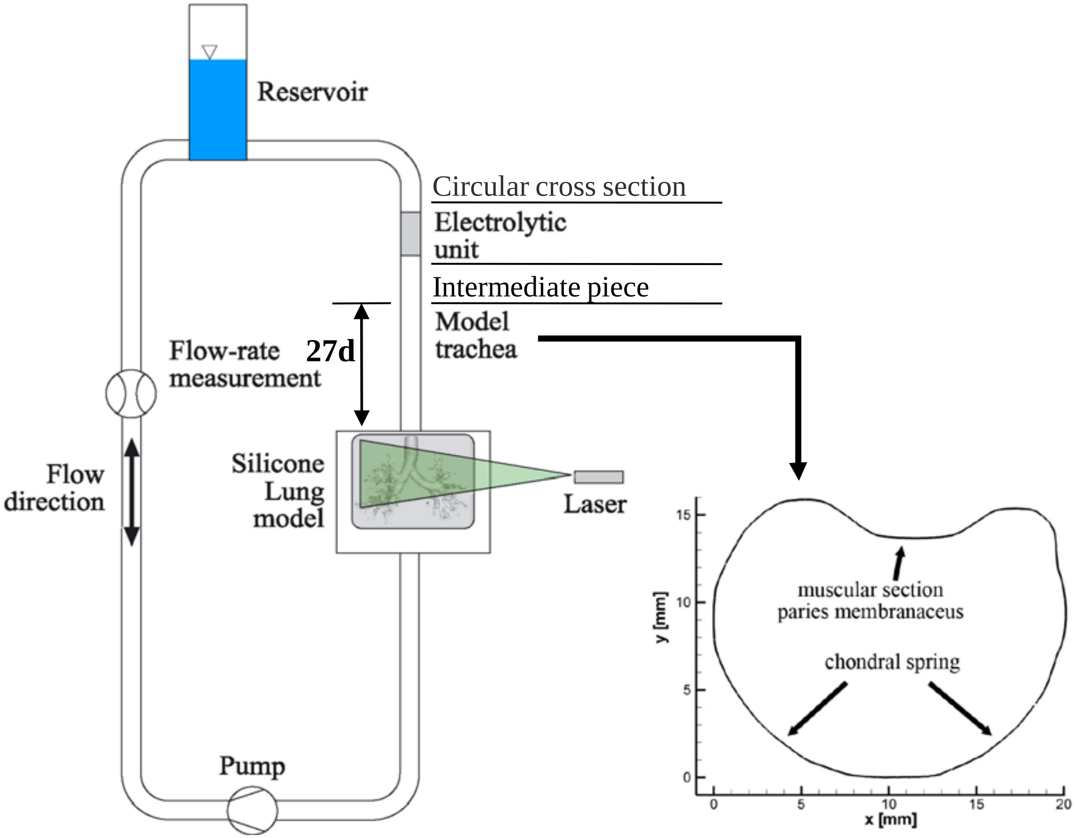
Corn starch model of the upper airways

Silicone block with corn starch model

Fully transparent model

1.4.2 Examination of the airway flow

Experimental setup for continuous flow



Fluid:
index-matched water-glycerin mixture

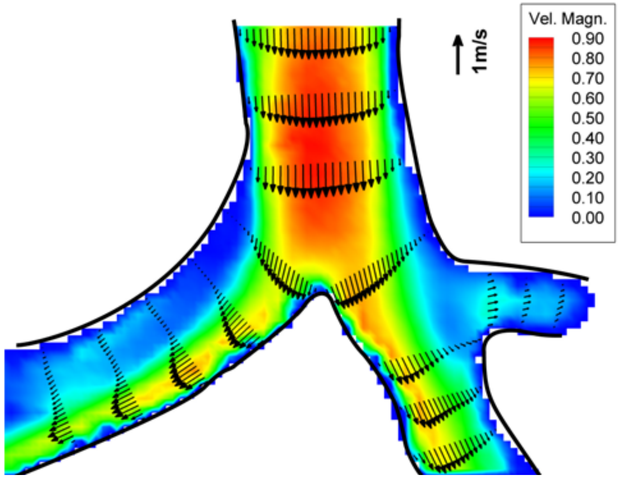
- 55 vol% glycerin (60.7 mass%)
- 45 vol% water (39.3 mass%)
- dynamic viscosity η: 0.0103 Pa·s
- density ρ: 1.154 kg/m^3
- refractive index n: 1.44

Tracer particles:
hydrogen bubbles

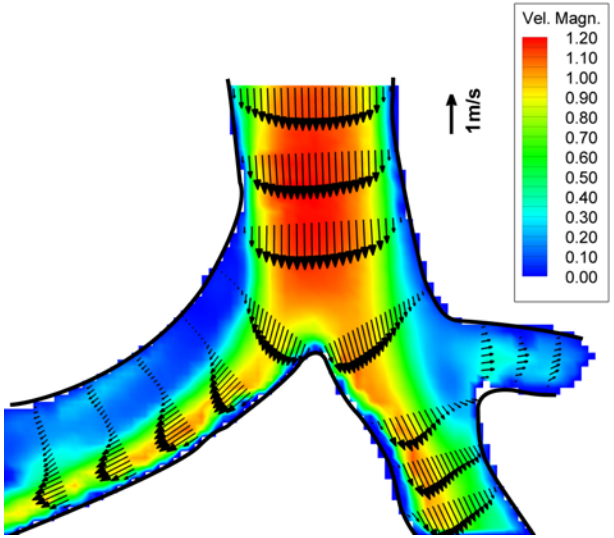
- particle size d_P: 1-5µm
- particle generation: Electrolytic unit

1.4.2 Examination of the airway flow

Results: continuous flow, inspiration – velocity magnitude and profiles



Re_D=1250

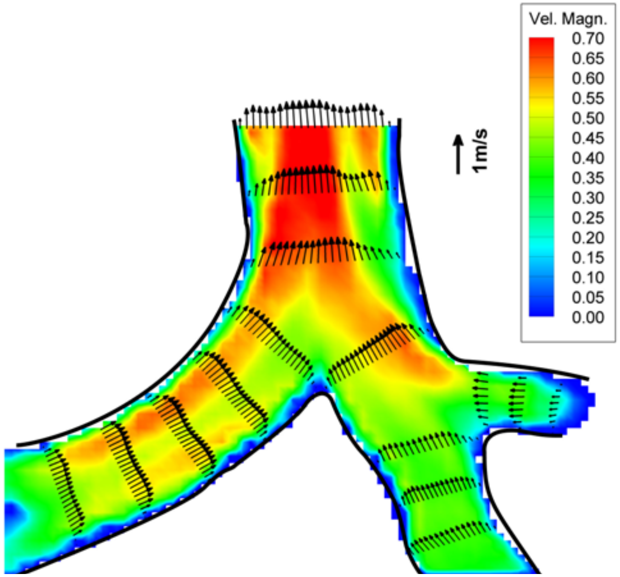


Re_D= 1700

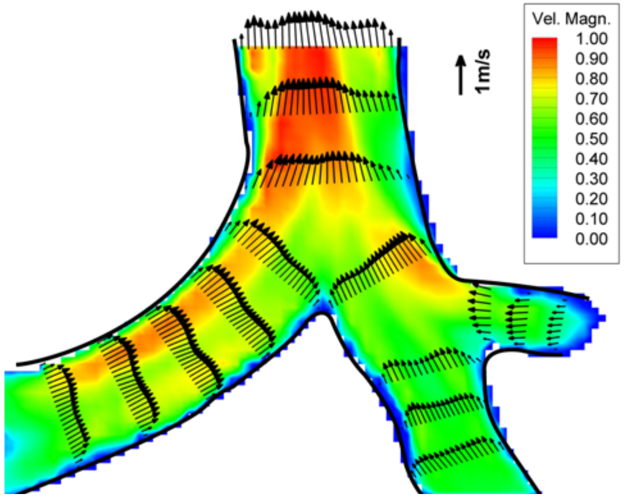
- Large zone of strongly reduced velocity in the left bronchia
- Two counter-rotating vortices in this region
- Jet-like high speed region along lower curve of the bifurcation
- Similar flow structures for both Reynolds numbers

1.4.2 Examination of the airway flow

Results: continuous flow, expiration – velocity magnitude and profiles



Re_D=1250



Re_D= 1700

- Flow field in the bronchia is strongly characterized by the inlet velocity from the sub-branches
- M-shaped velocity profiles in bronchia during expiration

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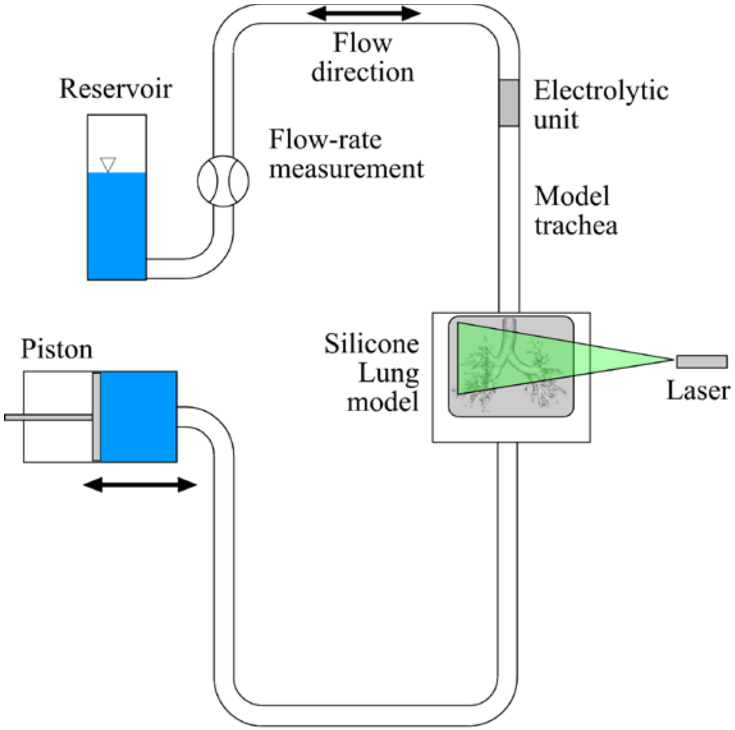
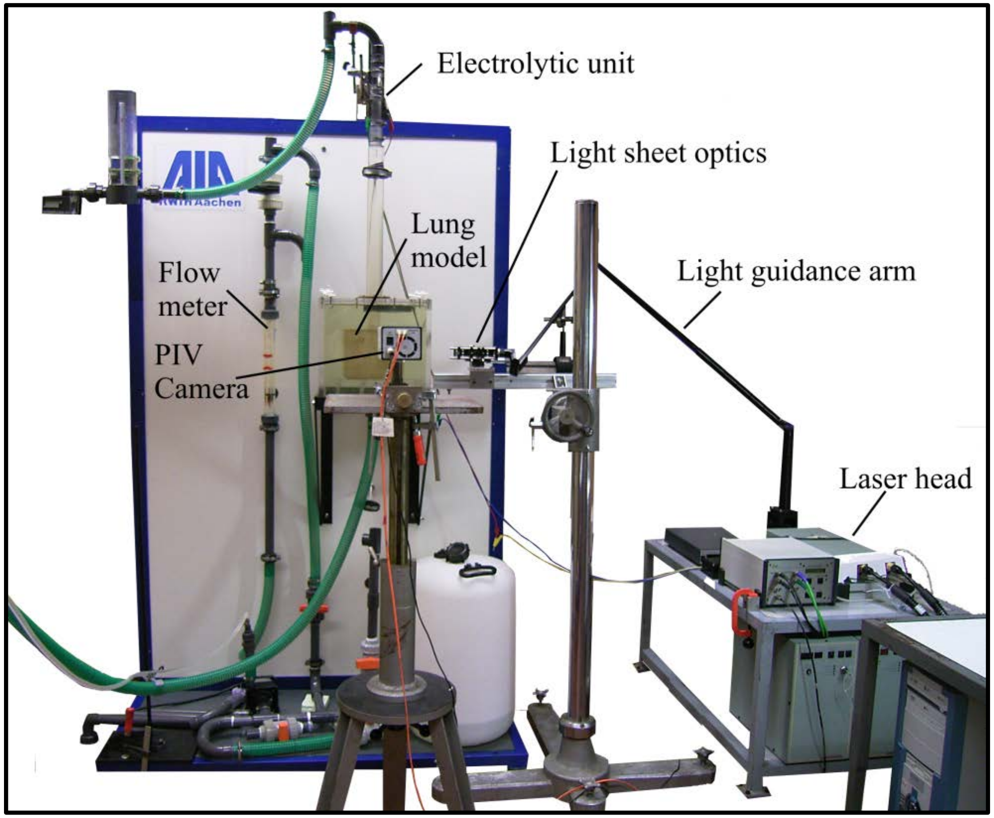
1.4.2 Examination of the airway flow

Experimental setup for oscillating flow





1.4.2 Examination of the airway flow

Experimental setup for oscillating flow

PIV System

- **Double cavity Nd:YAG-laser system: continuum Minilite PIV**
  - wavelength λ: 532 nm
  - repetition rate f: 15 Hz
  - pulse energy E_{max}: 125 mJ
  - pulse width: 3-5 ns
  - min. pulse distance Δt_{PIV}: 0.5 µs
- **Camera: PCO SensiCam QE**
  - resolution: 1376 (H) x 1040 (V)
  - pixel size: 6.45 µm x 6.45 µm
  - imaging frequency: 8 fps (full frame)
- **Vector processing software: VidPIV 4.6, ILA GmbH**

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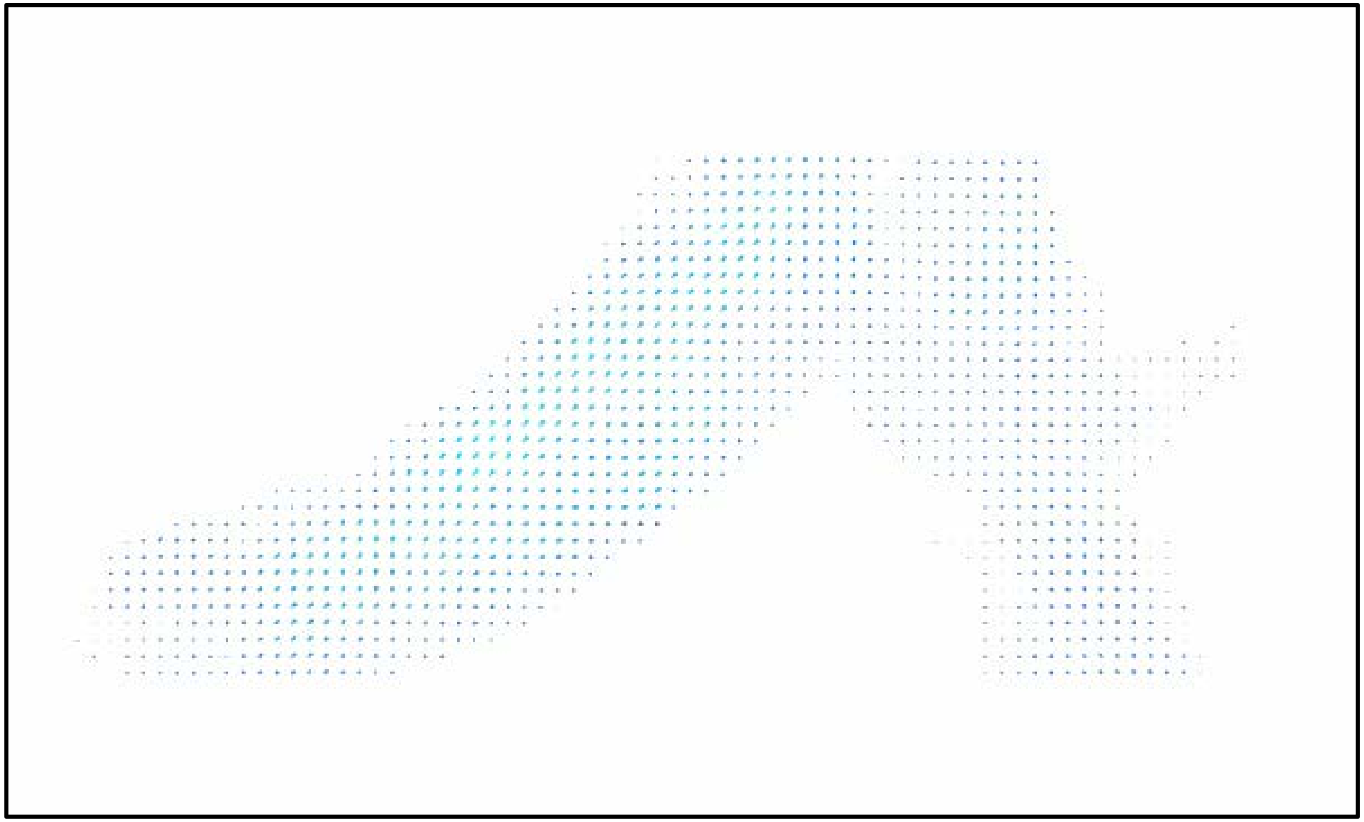
1.4.2 Examination of the airway flow

Results: oscillating flow, original vector size



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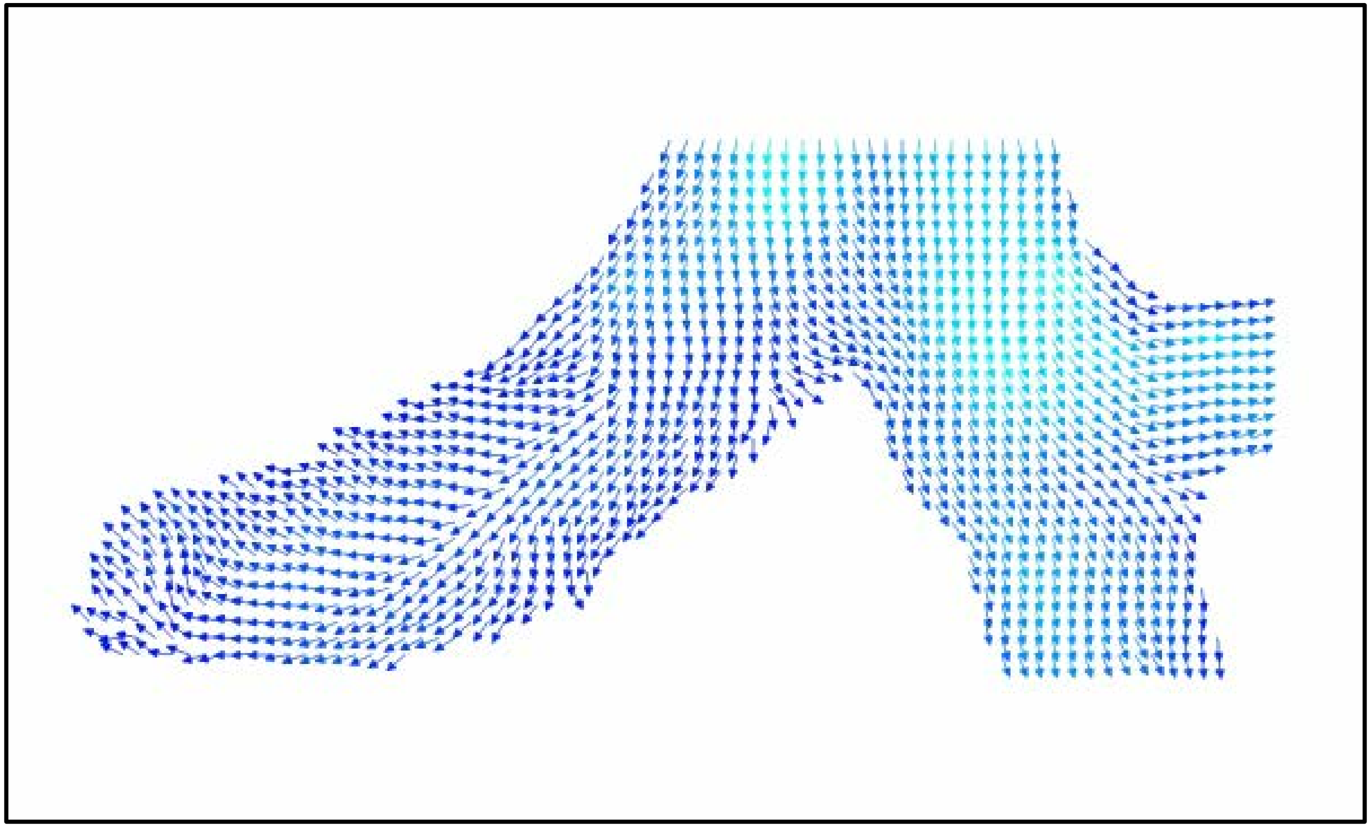
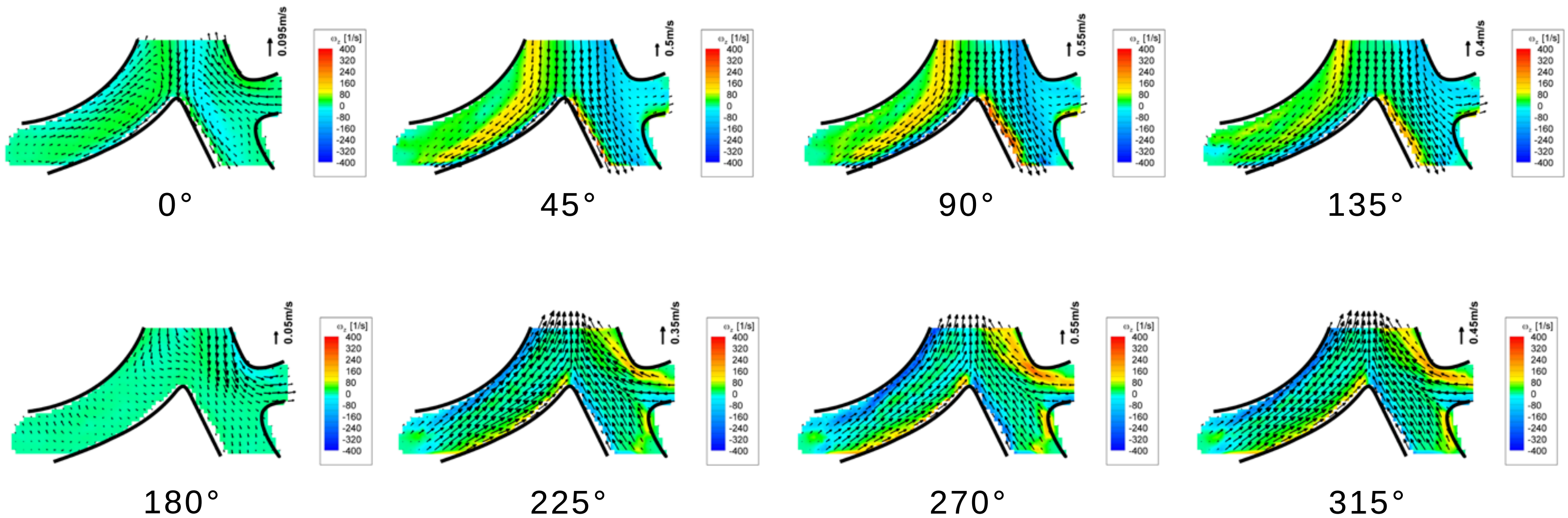
1.4.2 Examination of the airway flow

Results: oscillating flow, vector size normalized



1.4.2 Examination of the airway flow

Results: oscillating flow, inspiration & expiration



- max. Reynolds number Re_D: 2100
- Womersley number α: 3.27
- seconds per cycle: ~5.5

1.4.2 Examination of the airway flow

Results: oscillating flow

- **during inspiration:**
  - Large zone with two counter-rotating vortices
  - High-speed jets at the lower/inner bifurcation walls
  - Dead-water extends to the next generation of branches
  - Strong roll-up of the former vortical zone at the end of inspiration

- **during expiration:**
  - No dead-water zones in the bronchia
  - Moderate dead-water zones in the trachea

Lecture contents

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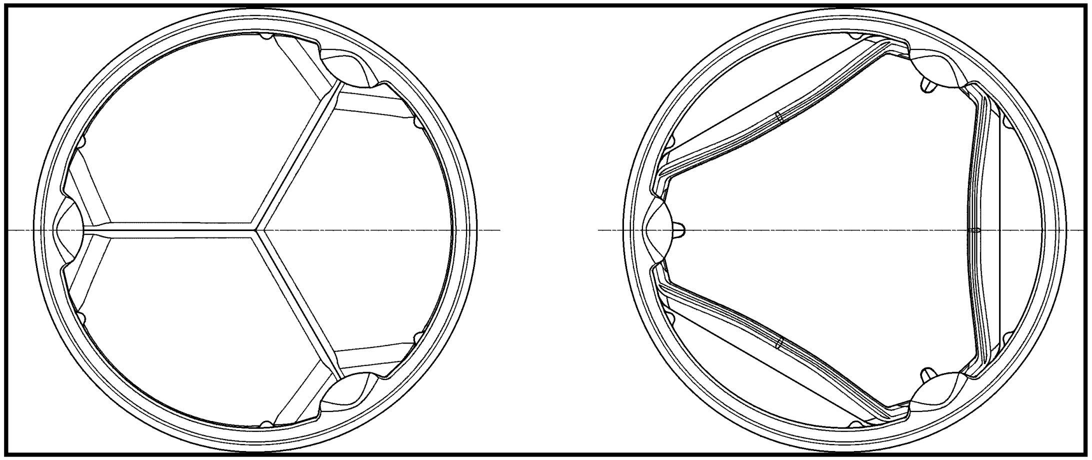
1.4 Examples of application 1.4.1 Computer assisted surgery of the nose 1.4.2 Examination of the airway flow 1.4.3 Investigation of an artificial heart valve 1.4.4 Silent flight of the owl	

1.4.3 Investigation of an artificial heart valve

Triflo© - Medical valve



- Design based on the human aortic valve with three sails
- Leaflets are S-shaped and move from 35° to 85° op. angle
- Early closure and reduced impact velocity
- Lower pressure loss and wider effective orifice area

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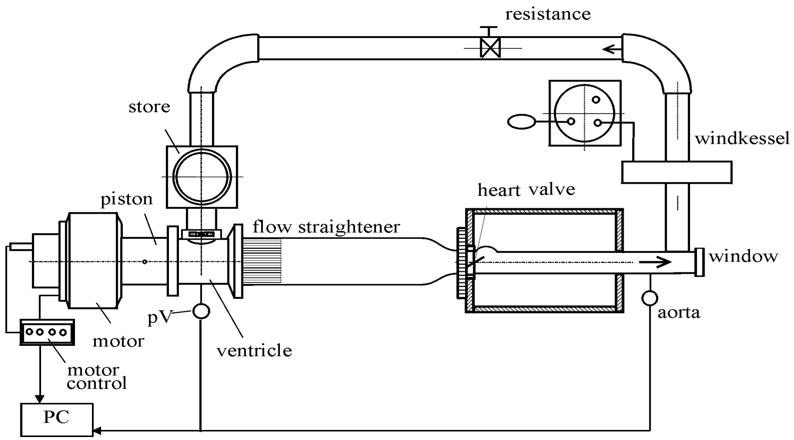
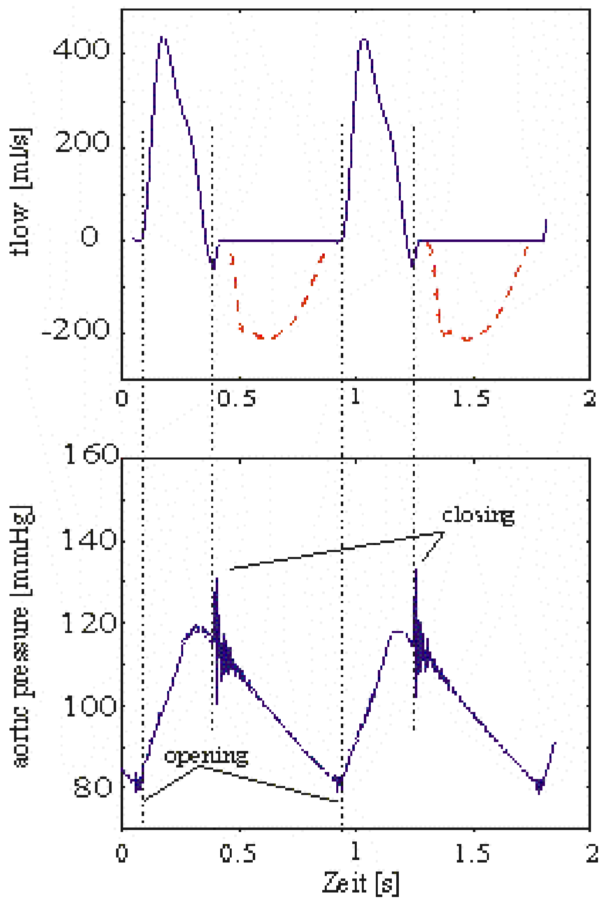
1.4.3 Investigation of an artificial heart valve

Pulsatile mock circuit for valve tests

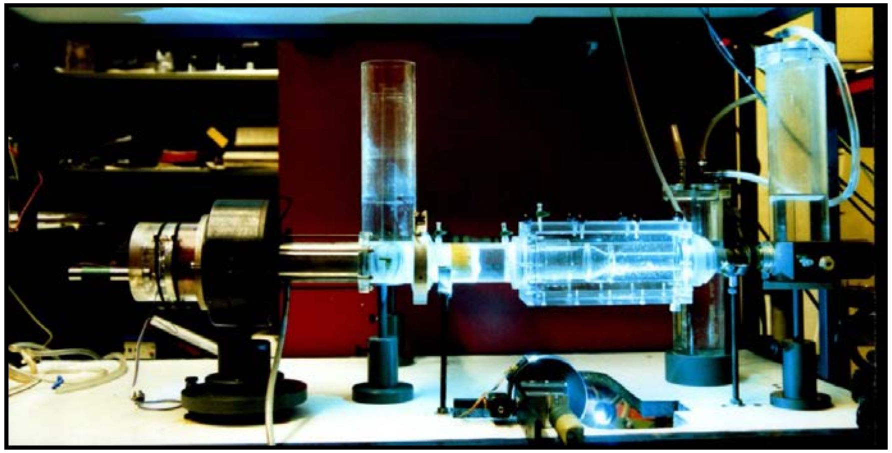




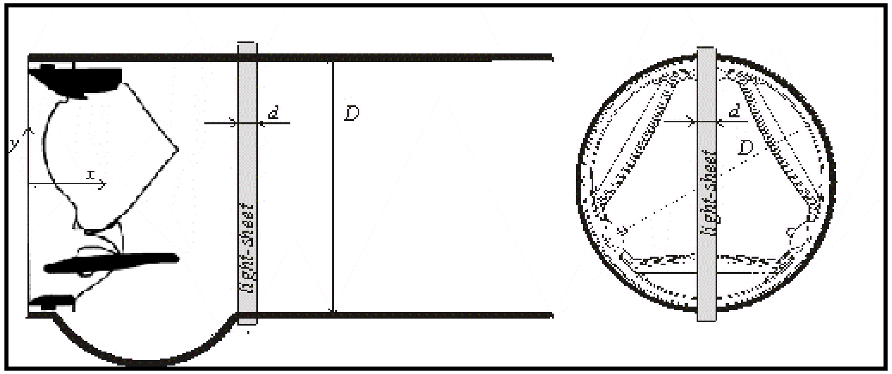
- Heart beat frequency: 50-150 beats/min
- Net stroke volume: 40-100 ml
- Rigid model of aorta and ventricle
- Use of newtonian test fluids
- Fully transparent plexiglas model of the valve
- Study parameters: 70 beats/min,
  70 ml stroke volume

1.4.3 Investigation of an artificial heart valve

Experimental setup



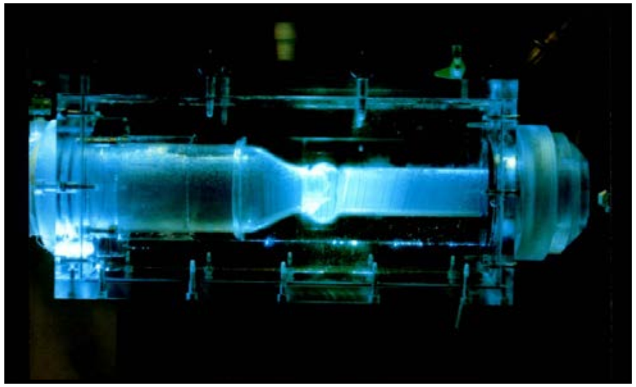
- **Time-resolved PIV recordings:**
  - 5 Watt Argon+ Ion Laser
  - Polygonal mirror illumination
  - Synchronized high-speed camera (Speedcam 512+)
  - Electronic gating



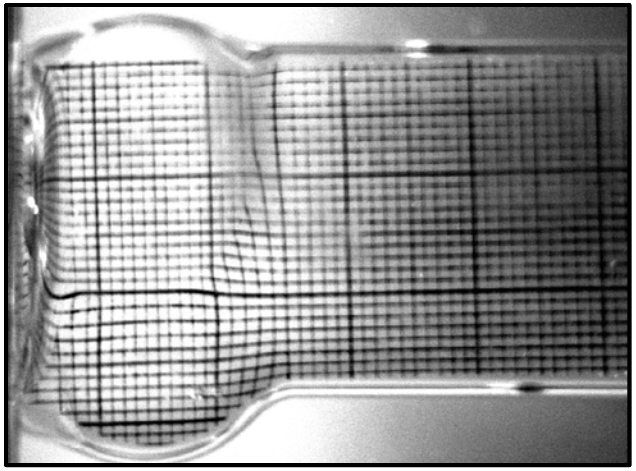
- **Phase-locked PIV recordings:**
  - Bragg-cell
  - Synchronized Nd:Yag laser
  - PCO camera

1.4.3 Investigation of an artificial heart valve

Calibration, optical distortion



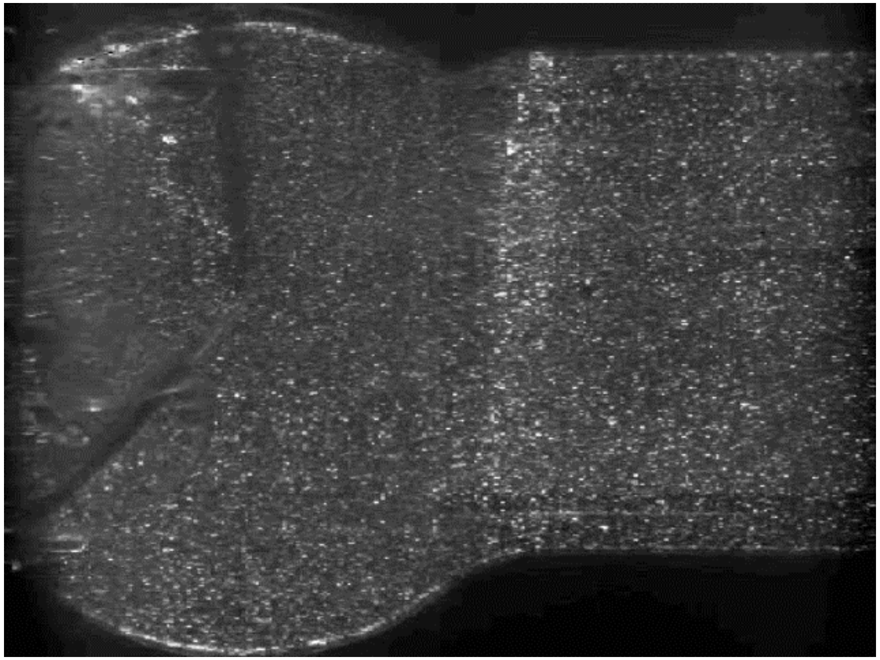
- **Refractive index matching**
  - Water glycerin mixture: n=1.44 at 20°C
  - Plexiglas: n=1.48



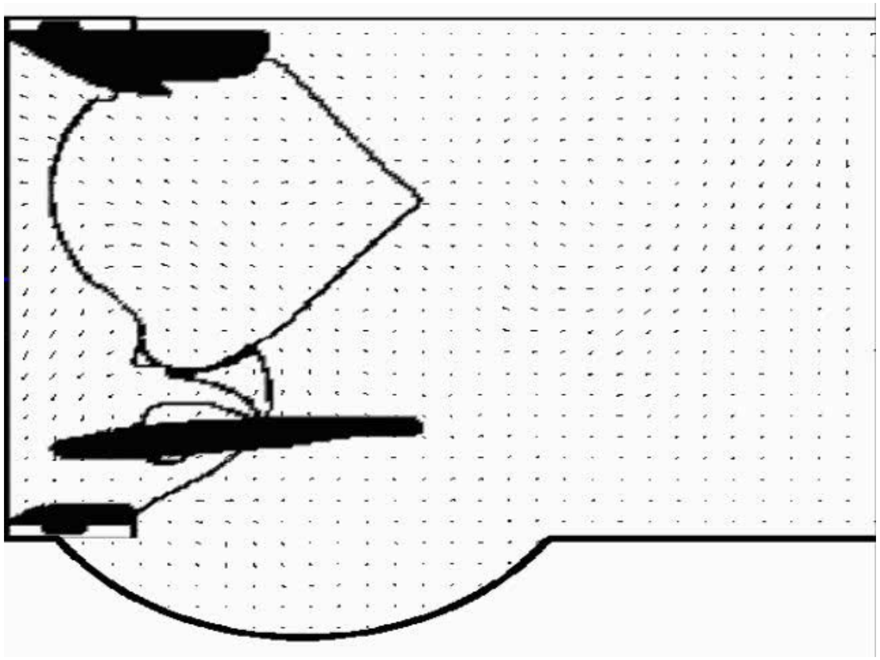
- **Calibration of remaining distortion:**
  - Recording of calibration grid
  - Detection of grid nodes and calculation of transfer function to a regular grid
  - Pixel-wise de-warping corresponding to the transfer function

1.4.3 Investigation of an artificial heart valve

Time-resolved PIV measurements
(High-speed digital video, 2000 fps, 512x512 px)



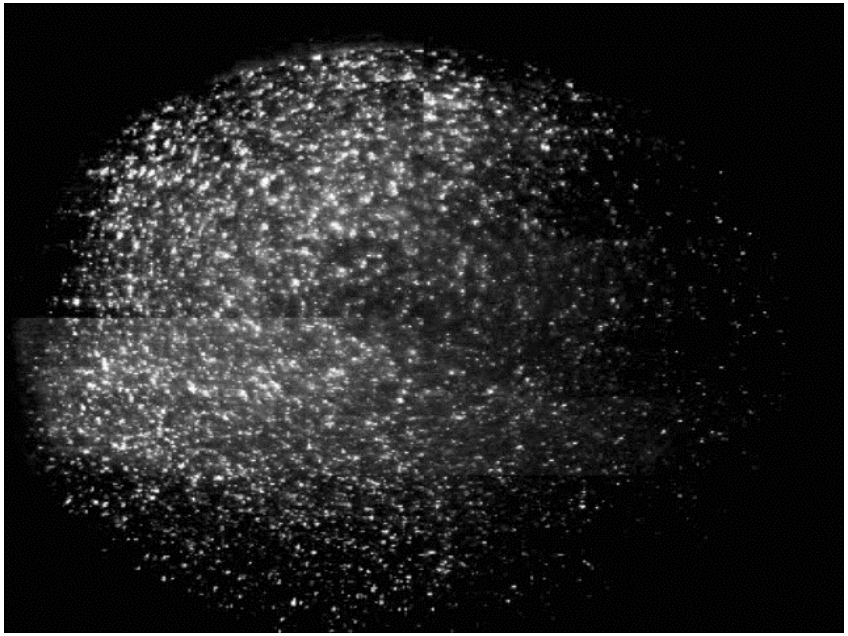
Original image



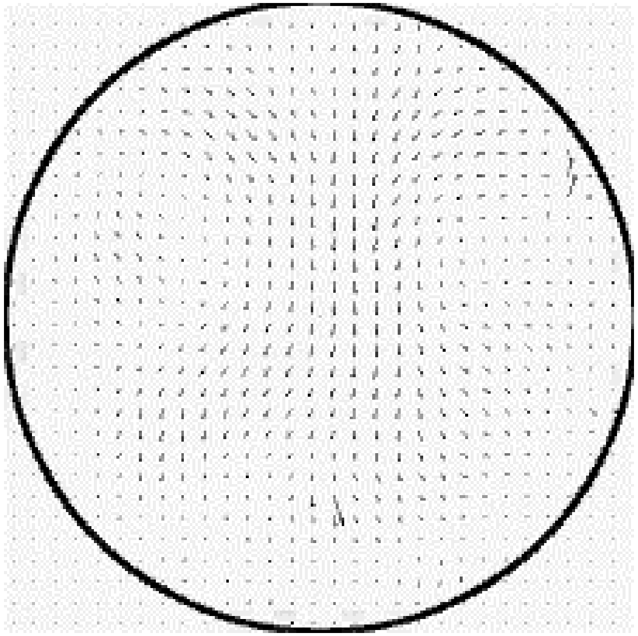
Velocity field

1.4.3 Investigation of an artificial heart valve

Time-resolved PIV measurements
(High-speed digital video, 1000 fps, 512x512 px)



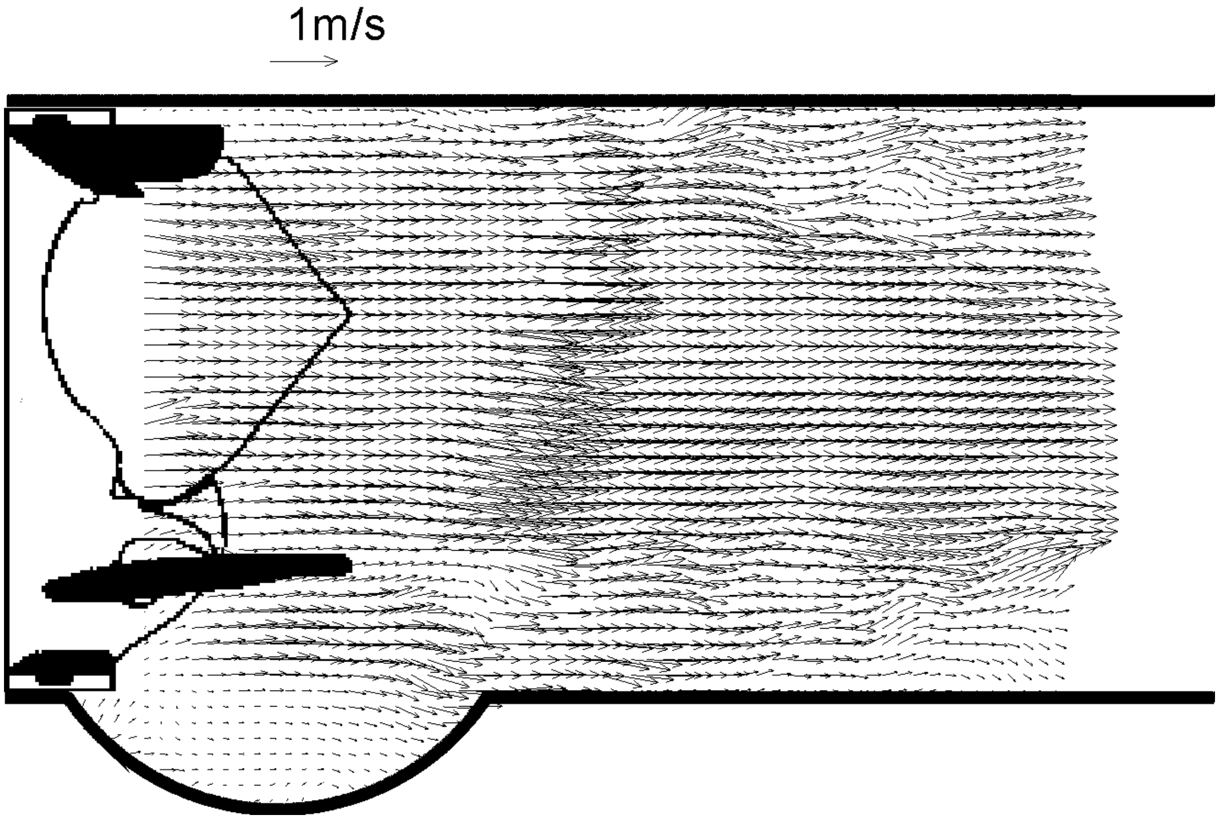
Original image



Velocity field

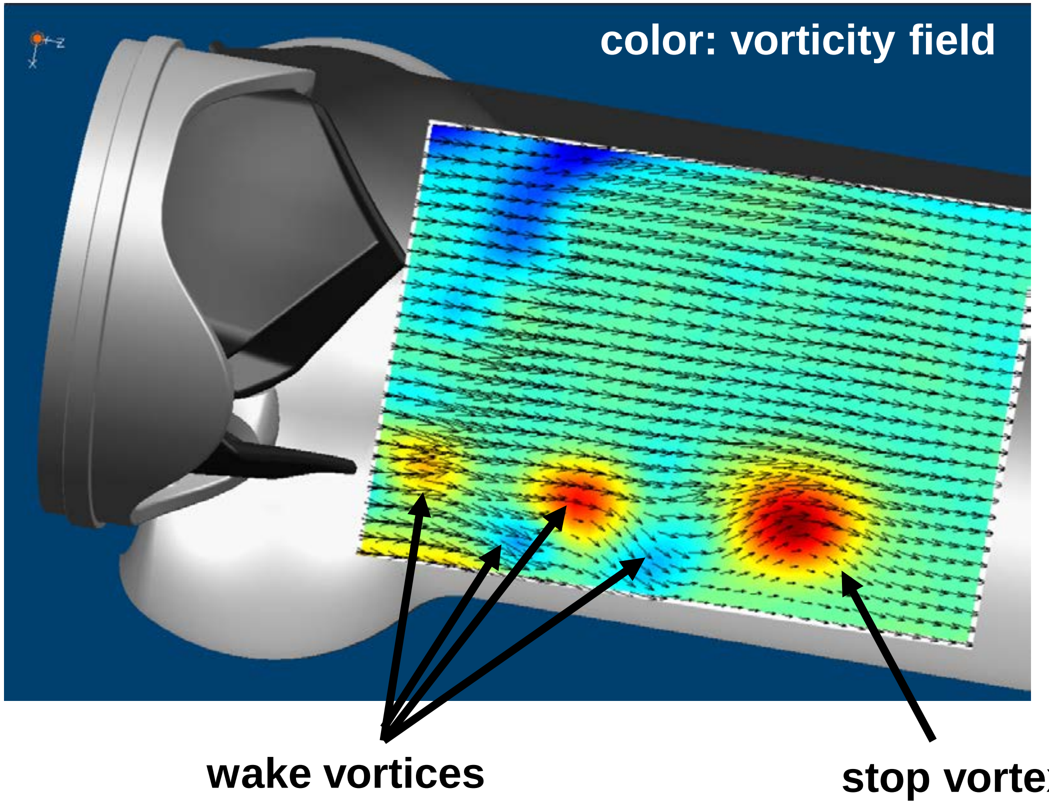
1.4.3 Investigation of an artificial heart valve

Instantaneous velocity field at peak



1.4.3 Investigation of an artificial heart valve

Vortical structures in the occluder



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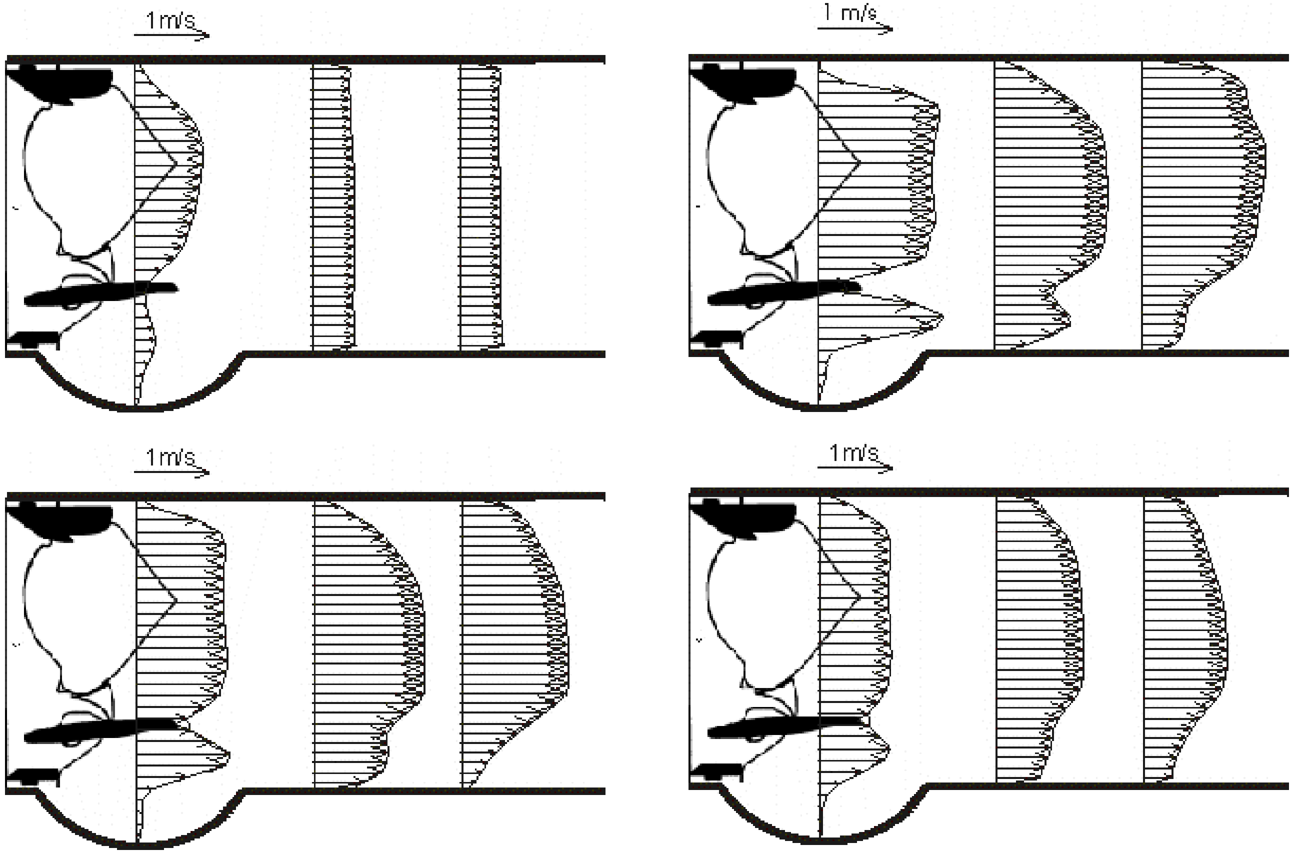
1.4.3 Investigation of an artificial heart valve

Axial velocity profiles (phase-averaged)



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1.4.4 Silent flight of the owl

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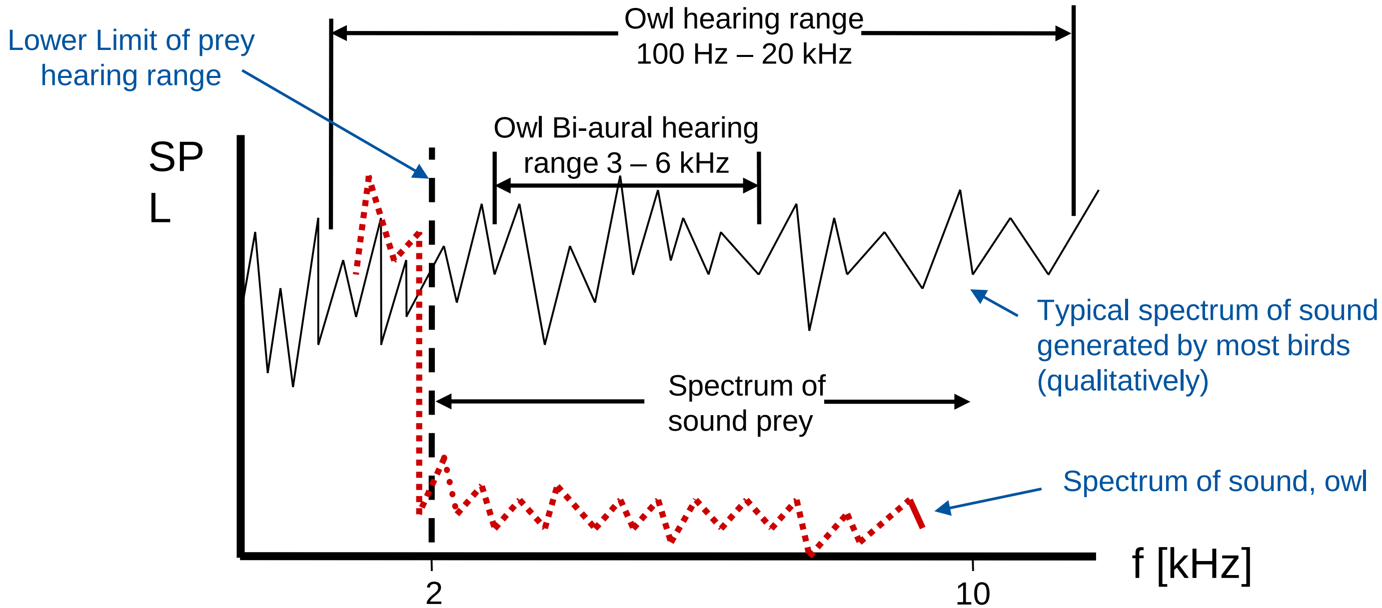
1.4.4 Silent flight of the owl

Special characteristics (McMasters 2004)

- Slow (and hence silent, sound ~ v^5) flight with high maneuverability
- Mechanism for sound reduction
- Significant sound reduction in the hearing range of prey
- Elimination of disturbances in the own hearing range



1.4.4 Silent flight of the owl

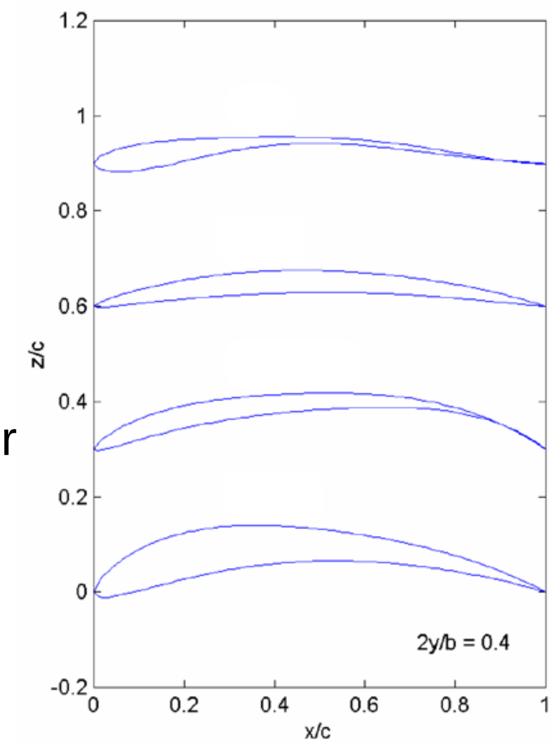
Airfoil sections of avian wings (Liu et al. 2004)

Owl

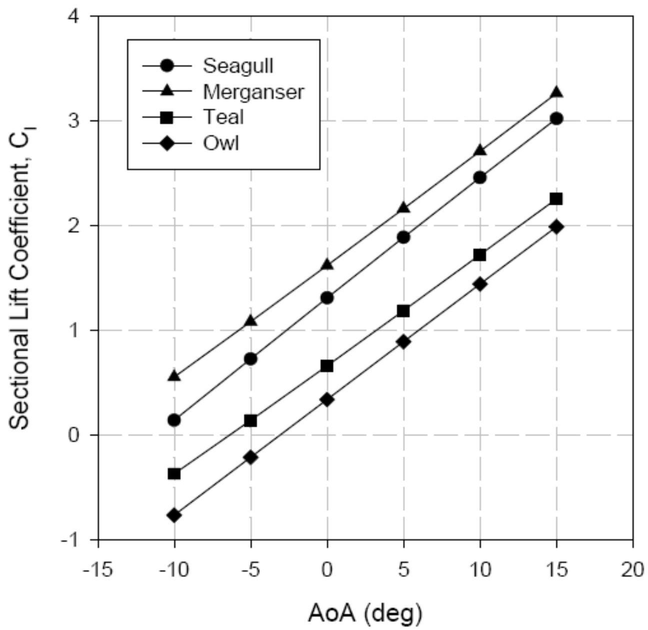
Teal

Merganser

Seagull



Airfoil sections

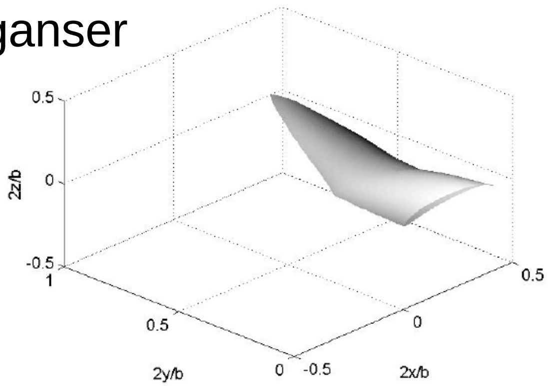


Lift coefficient

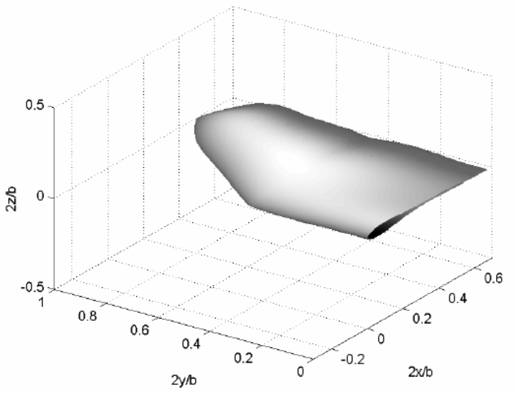
1.4.4 Silent flight of the owl

Wing planform of avian wings (Liu et al. 2004)

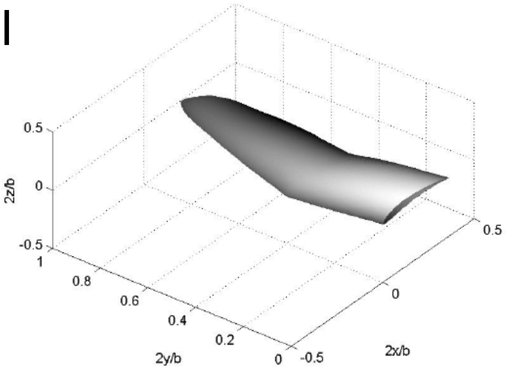
Merganser



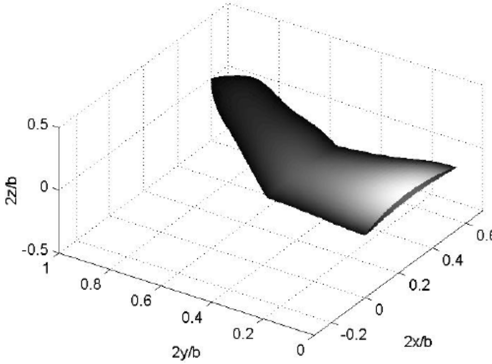
Owl



Seagull



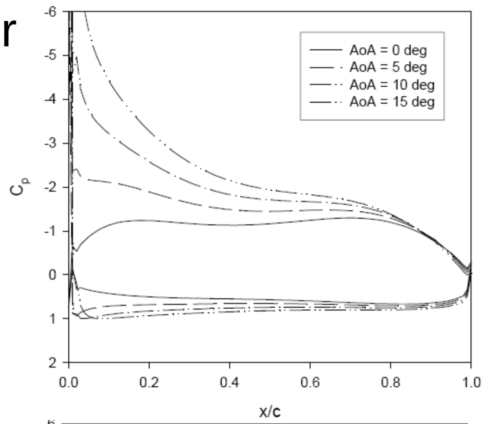
Teal



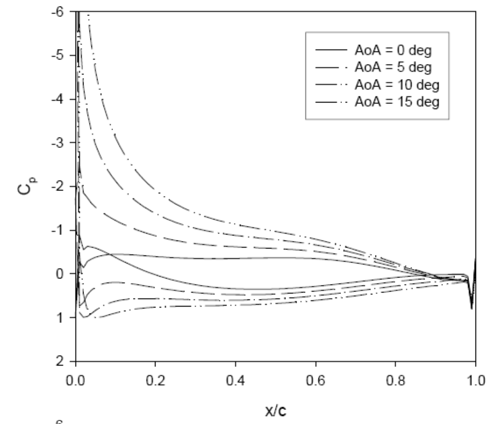
1.4.4 Silent flight of the owl

Pressure sistribution of avian wings (Liu et al. 2004)

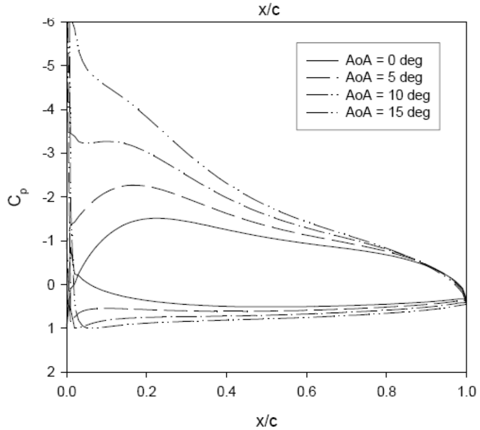
Merganser



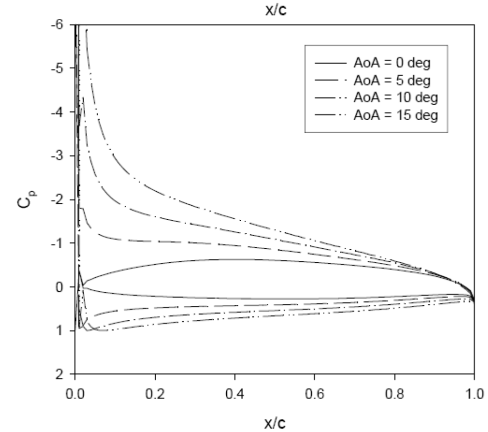
Owl



Seagull



Teal



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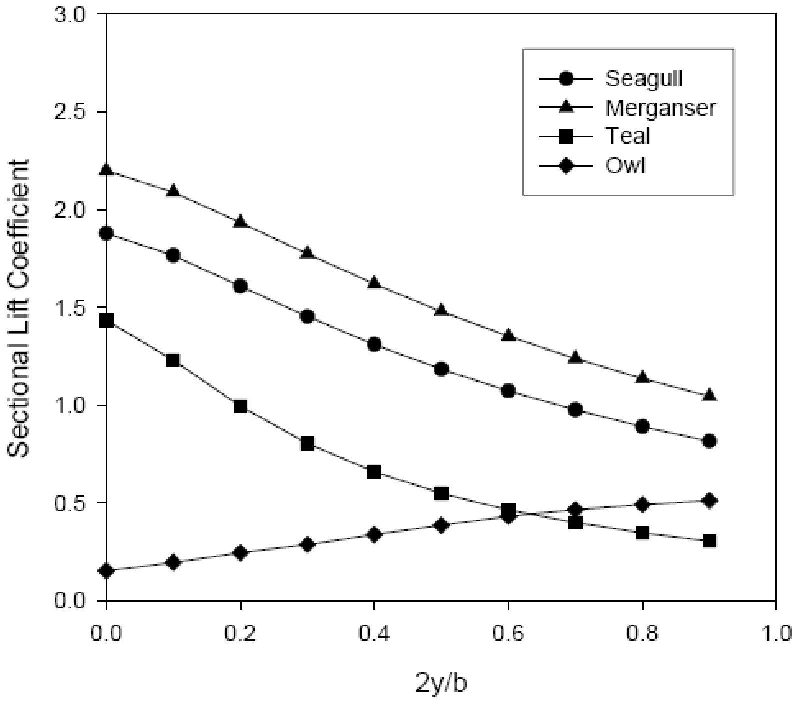
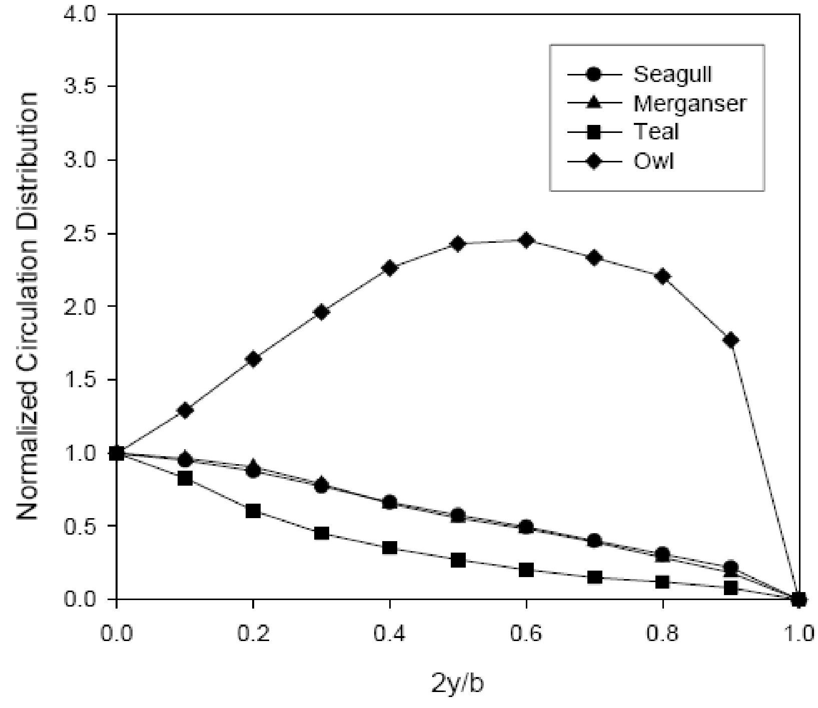
1.4.4 Silent flight of the owl

Circulation and lift of avian wings (Liu et al. 2004)





1.4.4 Silent flight of the owl

Special characteristics of the owl wing

- Maximum camber increases in spanwise direction
- Lower lift coefficient compared to birds with comparable size and weight
- Less than 2° twist in spanwise direction
- Thin profile for $0.3 \leq h \leq 1$
- Circulation distribution with parabolic shape

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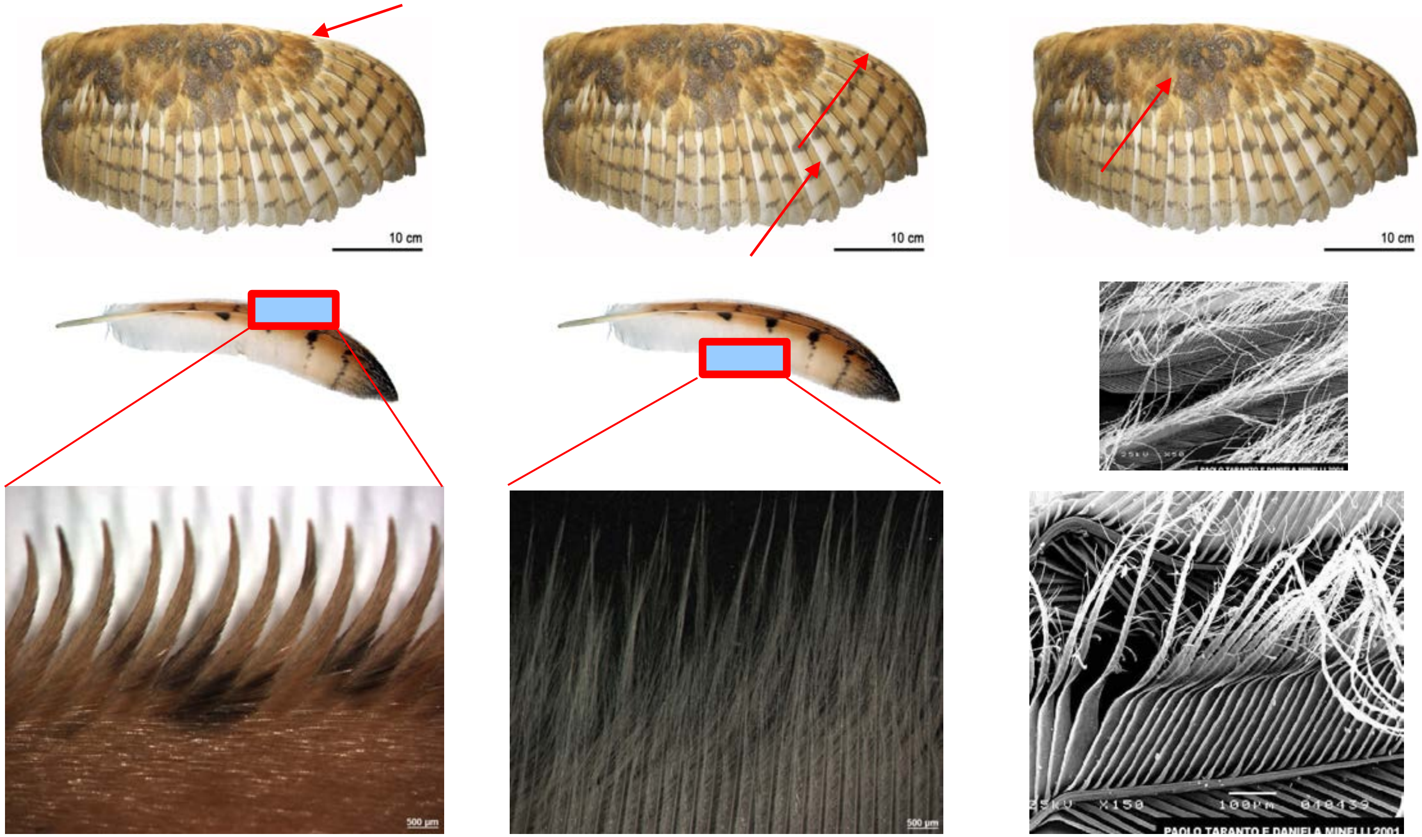
1.4.4 Silent flight of the owl

Special characteristics of the owl wing



1.4 Summary

1.4.1 Computer assisted surgery of the nose

- Geometrical changes have a greater influence on inhalation than on exhalation
- Laminar flow field as first approximation
- Steady flow field for Re > 700

1.4.2 Examination of the airway flow

- Large zones of reduced velocity in the outer regions
- Jets of high-speed fluid in the central regions

1.4.3 Investigation of an artificial heart valve

- Bulb flow without recirculation
- Regions of high vorticity downstream of the valve during opening/closing

1.4.4 Silent flight of the owl

- Silent flight through sound supressing mechanisms
- Further investigation necessary

Sources

[1] https://upload.wikimedia.org/wikipedia/commons/d/d4/Appareil_respiratoire_vierge.png

[2] https://en.wikipedia.org/wiki/File:TE-Nose_diagram.svg#/media/File:TE-Nose_diagram.svg

[3] Physiological Respiration through Standard Nose (R. Hincliff, D. Harrison)

[4] https://de.wikipedia.org/wiki/Lunge

[5] https://www.quora.com/Why-is-it-necessary-to-have-a-heart-that-constantly pumps-blood-in-a-human-body

[6] https://commons.wikimedia.org/wiki/File:Digestive_system_diagram_en.svg

Thank you for your attention!