Respirator Models to Analyze Sensor Placement and Fit

NIOSH/NPPTL Public Meeting

Pittsburgh, PA
September 17, 2009

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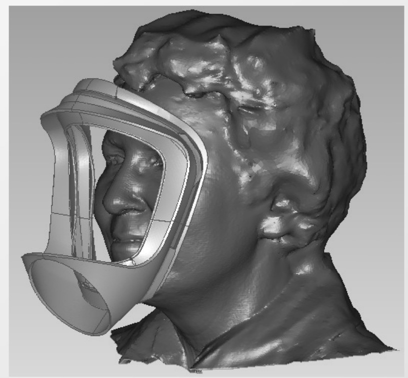
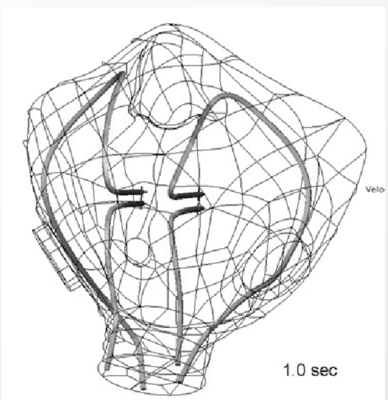
DHS Projects on Respirator Modeling

Characterizing Respirator Fit
for Real Faces and Masks





Respirator Sensor Placement
for Accurate Readings

Sponsored by U.S. Department of Homeland Security
Science & Technology Directorate
under contract HSHQDC-08-X-00414

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Fire Fighter Respiratory Protection

- Respirators must protect against many hazards
  - Particulates, chemical and biological toxins
  - Lack a priori knowledge of threats
- Wide range of situations
  - Normal and high stress
  - Short duration: fire suppression
  - Long duration: salvage and search and rescue
- Issues
  - Imperfect fit
  - Leaks
  - Heavy breathing and coughing

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Issues

Imperfect fit

- Annual fit test - good enough?
- Variation over time

  (Month-to-month, wearing-to-wearing, minute-to-minute?)
- What are the consequences?

Leaks

- Do they happen?
- Under what conditions?
- Occasional? Individual?

Sensor for real-time monitoring

- Good idea? State of technology?
- Where would it be placed?

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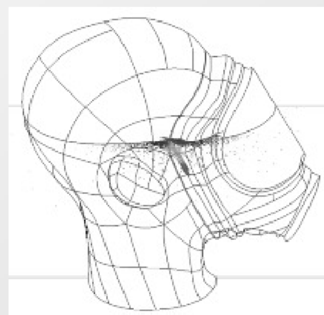
Computational Models

- Can test variety of situations
  - Breathing pattern
  - Leak geometries
  - External environments
  - Contact between face and mask



- Visualization of results
  - Velocity
  - Pressure
  - Particle traces
  - Gas concentrations

1st step: Need to define the complex geometry of a person wearing respirator

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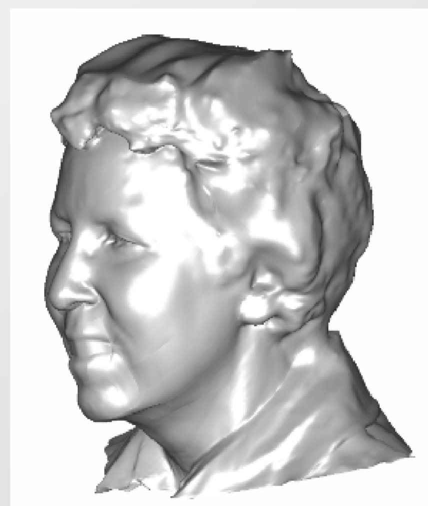
Head Geometry
3D Scanner

3D scanner

3D point cloud

Smoothed, holes filled

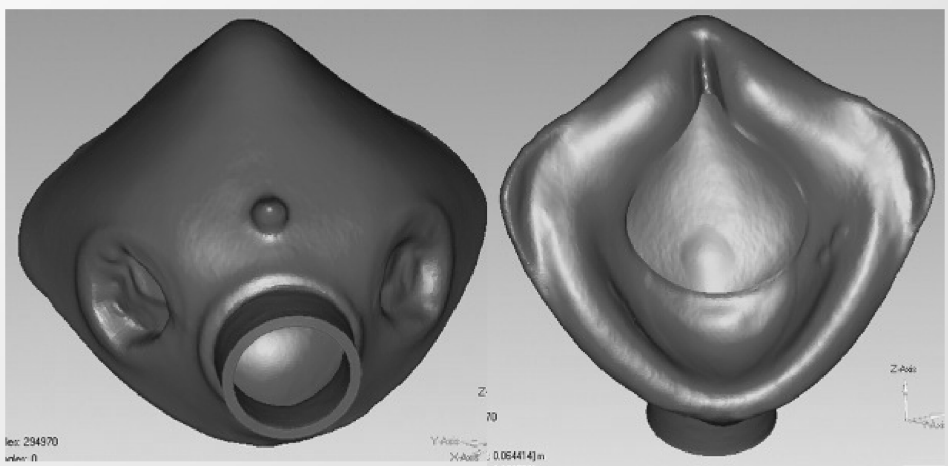


Mouth open

Mask Geometry

3D Scanner

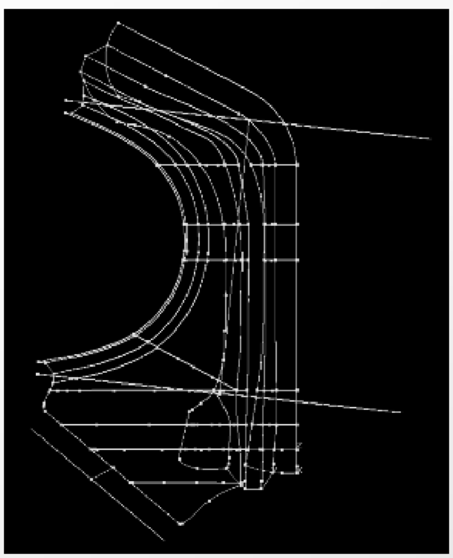
3D point cloud



Smoothed, holes filled

Mask Geometry

Mechanical Drawings



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Mask Geometry
CAD

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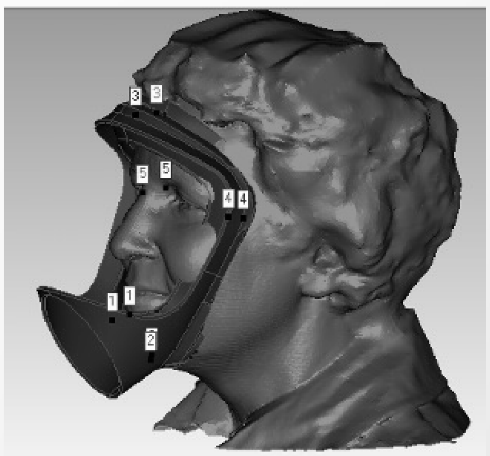
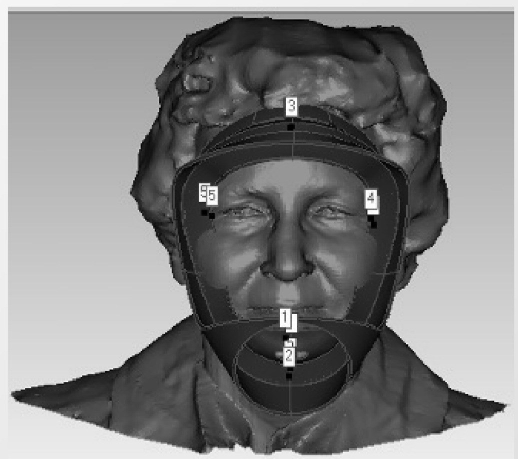
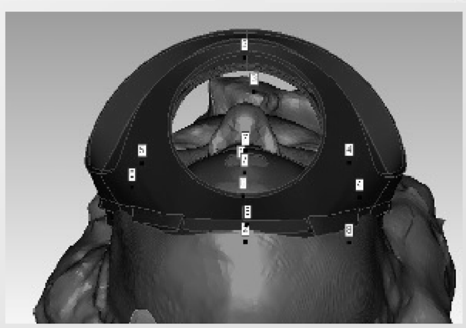
Combining face and mask
- the easy way doesn't work







How can we characterize fit and discomfort for a given individual and a respirator?

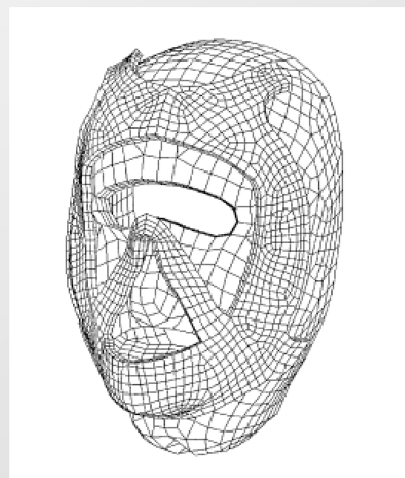
Computationally push respirator onto face, taking into account

- Material properties of respirator
- Material properties of skin over bone

Contact pressures indicate regions of potential leaks or discomfort

How good is a rigid 3D scan for predicting fit?

How difficult would it be to customize the seal?



Piccione and Moyer, 1997

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Project: CHARACTERIZING RESPIRATOR FIT FOR REAL FACES AND MASKS (K. Butler, M. Smith)

Issue: Importance of fit and comfort for respiratory protection

- Emergency responders can overbreathe respirator at high work rates. Without a good fit, respiratory protection is compromised and leaks can occur.
- Emergency responders are willing to discard protective equipment when they believe it impedes their ability to do their jobs. Comfort is critical to wearability, especially during long operations.
- The use of rigid 3D head scans or physical headforms for testing and sizing respirators do not take properties of skin and bone into account.

Purpose

- To enhance respirator fit and sizing procedures by improved knowledge of the relationship between human and respirator features and respirator effectiveness

Approach

- Characterize the relationships between respirator fit, respirator discomfort, and the geometry of faces and respirators using the actual material properties of rubber or silicone seals and skin over bone

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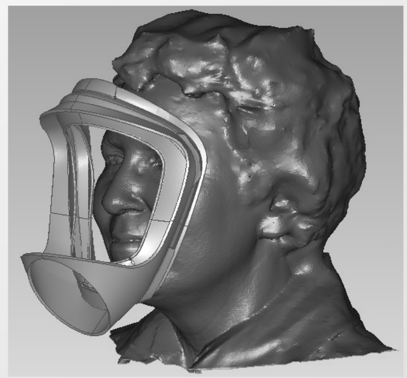
Technical Approach

- Prepare 3D representations of respirator masks and human heads
- Push flexible mask onto face computationally for multiple pairings, plotting stresses on the contact surface to find locations of possible leaks and fit comfort
  - Rigid face
  - Skin over rigid face
  - Skin over rigid bone from medical scans



- Animate face and determine position or motion of jaw most likely to result in a leak
- Assess sensitivity to mask positioning, material properties, and design factors.
- Assess ability of fixed 3D head scan to evaluate goodness of fit in comparison with actual material properties of face. Recommend improvements in respirator sizing procedures and changes to standards.

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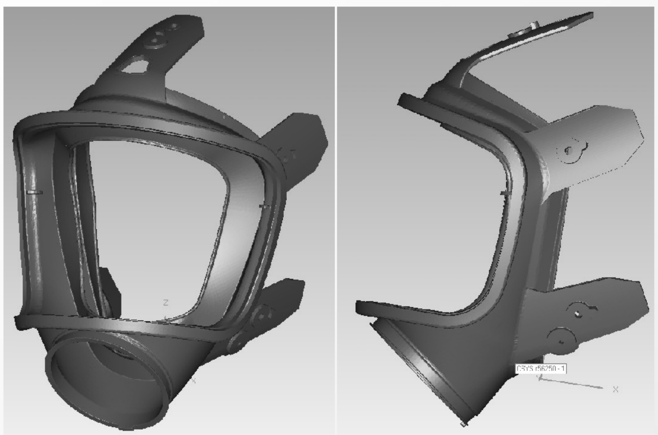
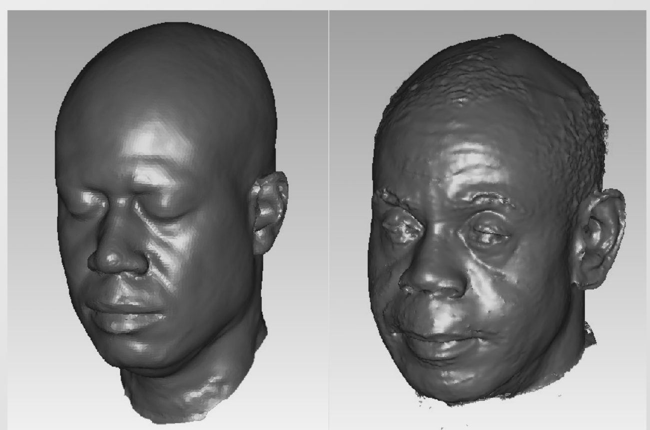
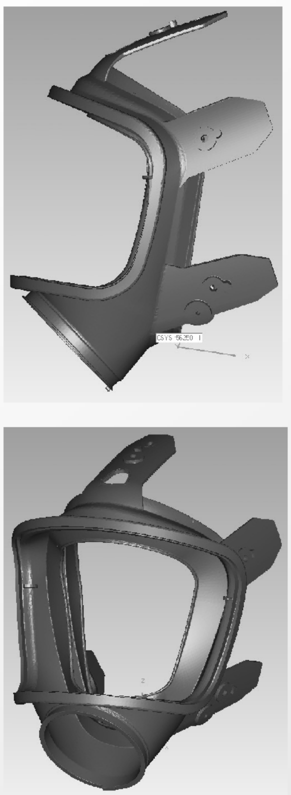
Variety of respirators and faces

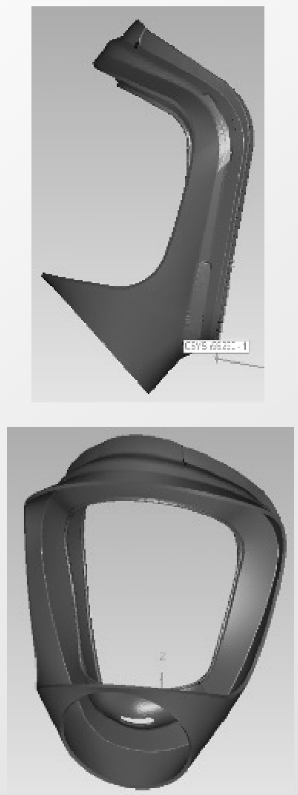




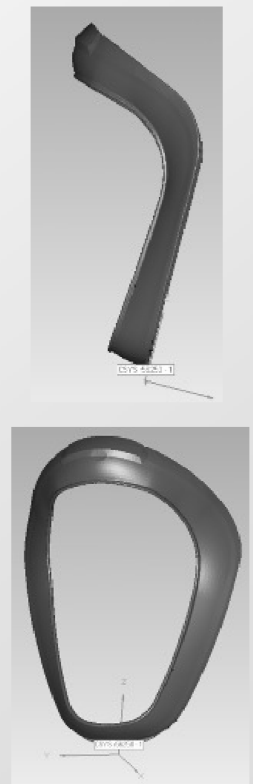
Respirator Seal Geometry



CAD

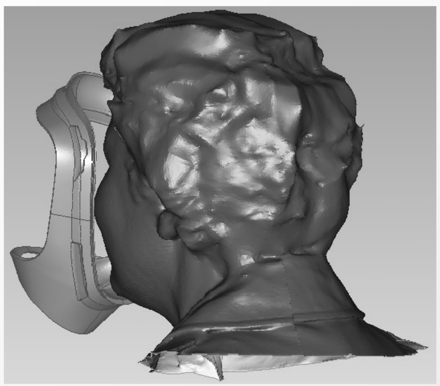


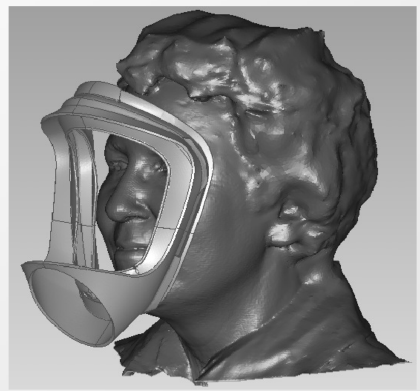
Full seal

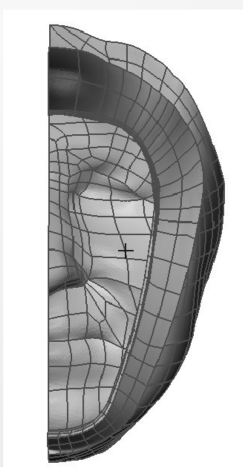


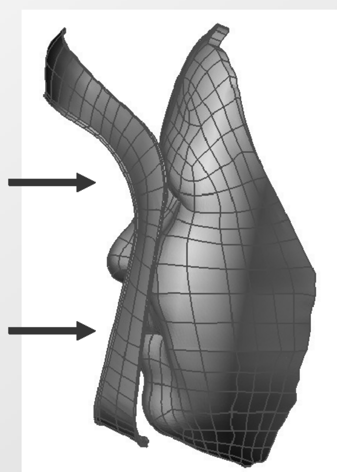
Single seal

Technical Approach





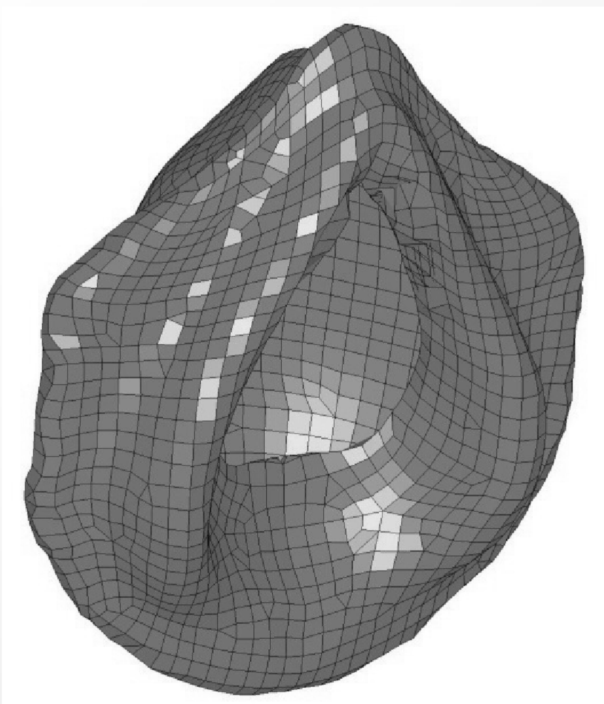


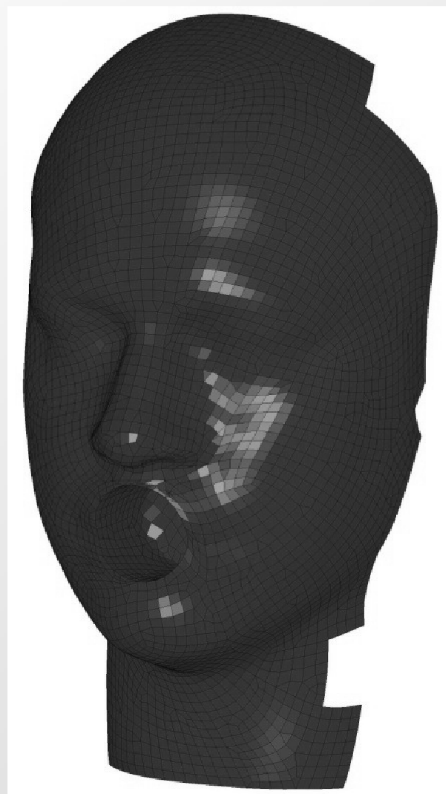


Finite Element Method (FEM)

Contact problem

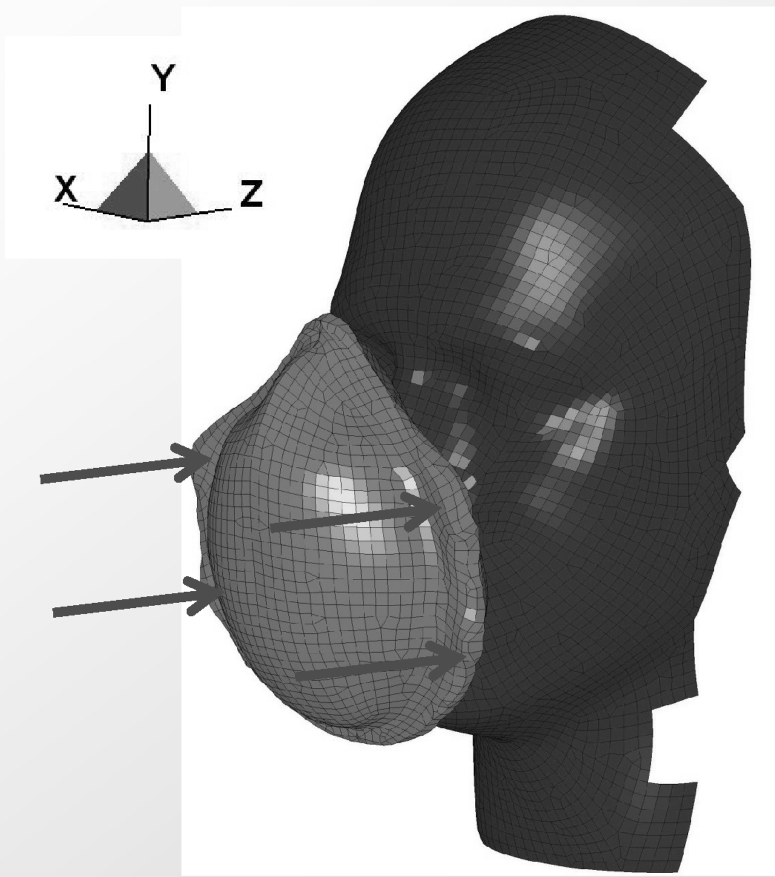
Jingzhou Yang - Texas Tech University



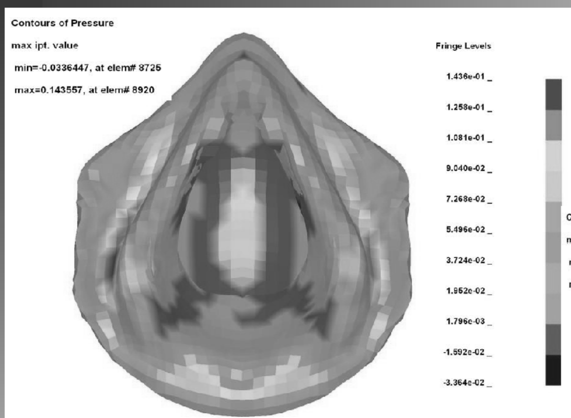


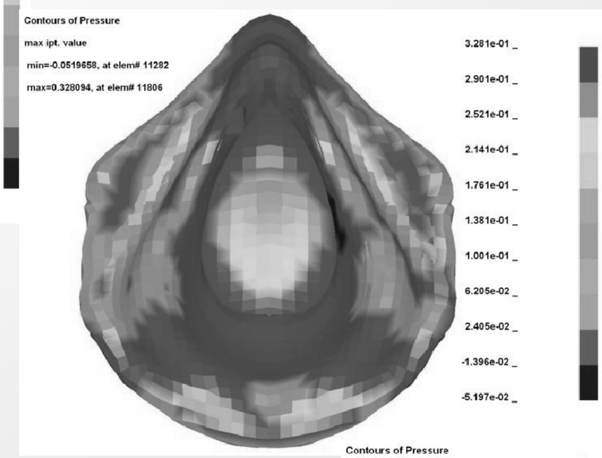
J. Yang, J. Dai, Z. Zhuang, *Computer-Aided Design and Applications*, 2009.

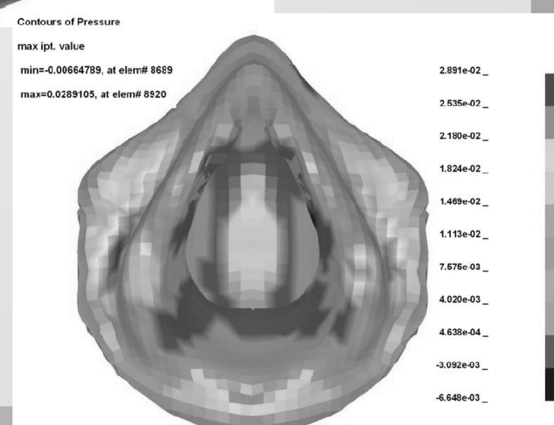
Apply 2.5 N (5 N) force to each strap



Pressures on Respirator







2.5N on each strap

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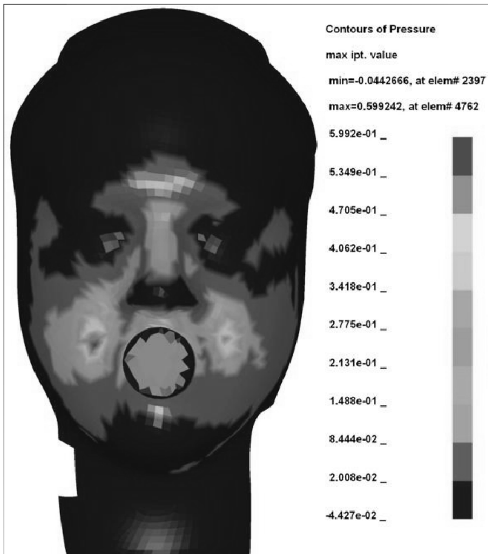
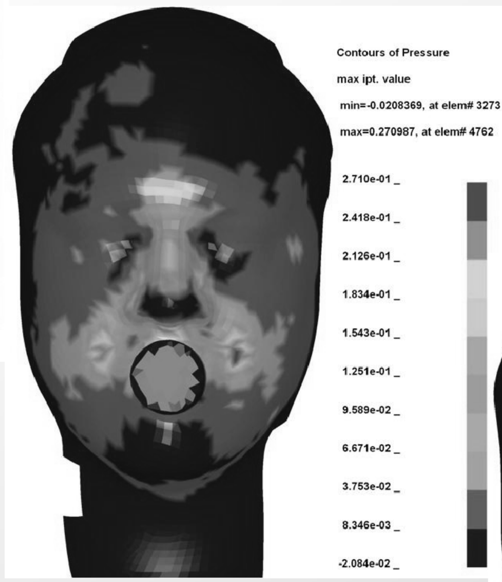
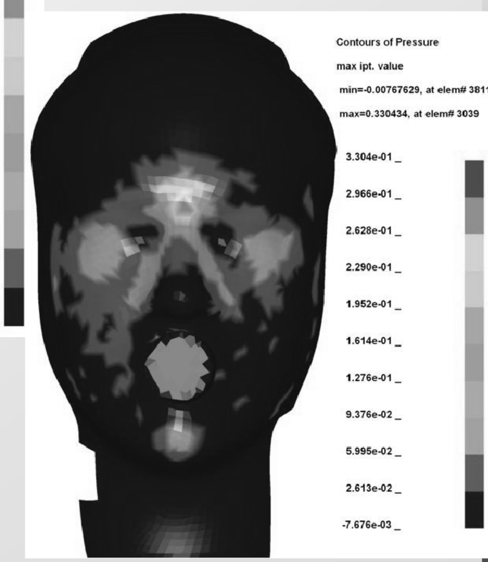
Pressures on Face







2.5N on each strap

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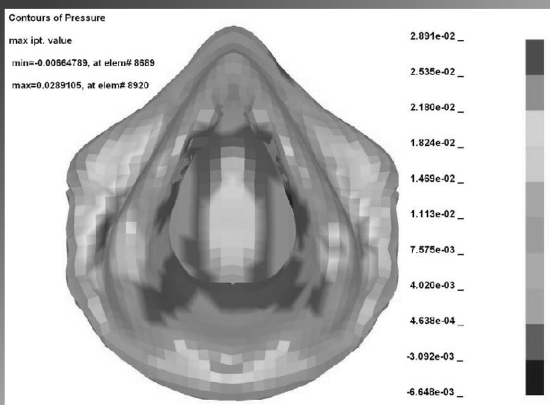
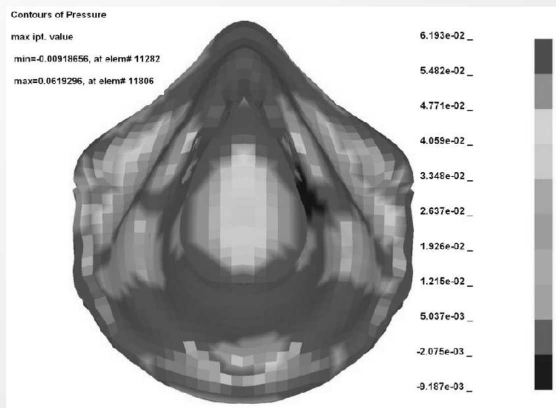
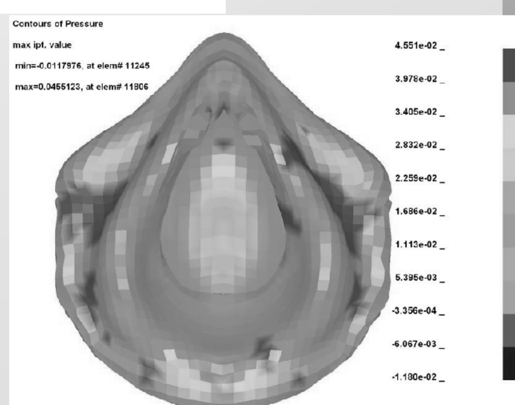
Pressures on Respirator

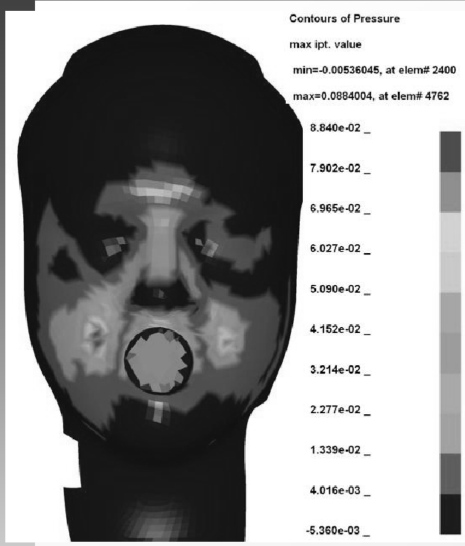


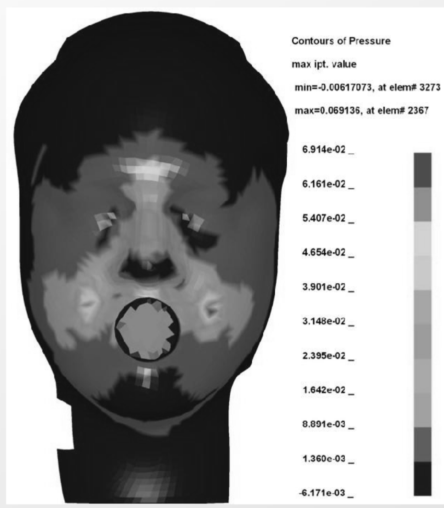


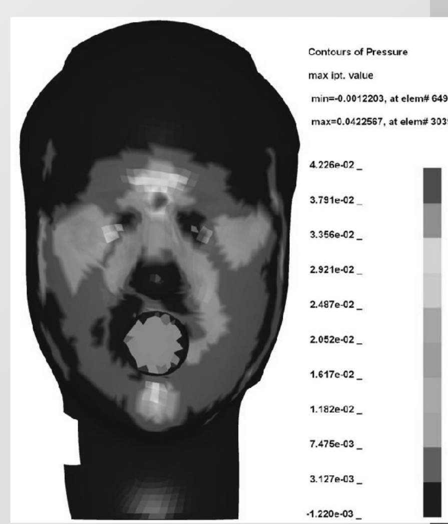
5 N on each strap



Pressures on face







5 N on each strap

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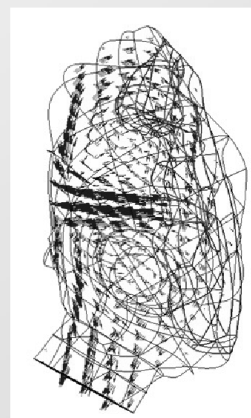
What are the possibilities for real-time respirator monitoring?

- Where are the best positions for monitoring flow, pressure, gas concentrations?
- How is the flow affected by a leak?
- What breathing resistance does the user experience?



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Project: RESPIRATOR SENSOR PLACEMENT FOR ACCURATE READING (K. Butler, M. Nyden, R. Bryant)

Issue: Real-time monitoring

- Monitoring of conditions inside a respirator would provide immediate warning of a leak. The emergency worker could then be removed from a dangerous situation.
- For readings that accurately and rapidly reflect the respiratory intake of emergency worker, the sensor must be placed in a region that sees the flow but is not disturbed during respirator use.

Purpose

- To evaluate the need and potential sensor technologies for real-time monitoring of emergency responder respiratory intake, and to provide criteria and recommendations for placement of sensors in respirator masks

Approach

- Determine locations within a respirator mask that are suitable for placement of a sensor for real-time monitoring of respiratory intake, using computational methods validated by experiment

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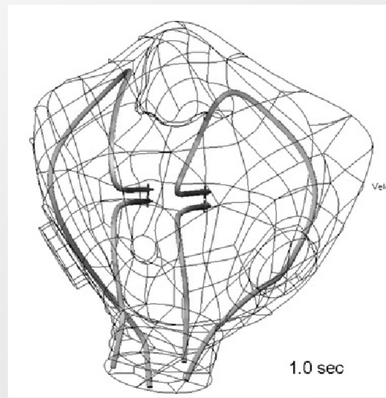
Technical Approach

- Conduct a workshop to discuss the need and potential solutions for real-time monitoring of emergency responder respiratory intake.
- Prepare 3D representations of actual heads and half and full facepiece respirator masks, and define the region of flow between facepiece and face.



- Solve for the flow field and pressure field for multiple head-mask combinations, low and high work rates, and a variety of leaks
- Validate the model against experiment
- Determine criteria and potential locations for sensors to perform real-time monitoring of breathing intake, and incorporate results into a standard for monitoring device placement

Workshop

Real-Time Monitoring of Total Inward Leakage of Respiratory Equipment Used by Emergency Responders
1 May 2009

- ~25 attendees
  - Firefighters, researchers (sensors and respirators), manufacturers, standards committee representatives
- Addressed the critical issues
  - What is the need?
    - Potential uses: Is there a leak? Can the respirator be removed? Data collection, physiological monitoring
    - Possible approaches: outside or inside mask, mounted on gear, multiple measurements
  - What sensor technologies are available?
    - Measure gas species, particulates, pressure
  - What challenges must be met?
    - Confounding factors, unknown environment, trust of users

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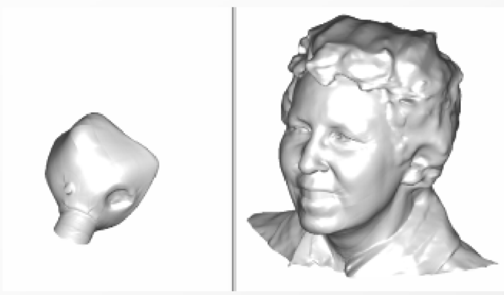
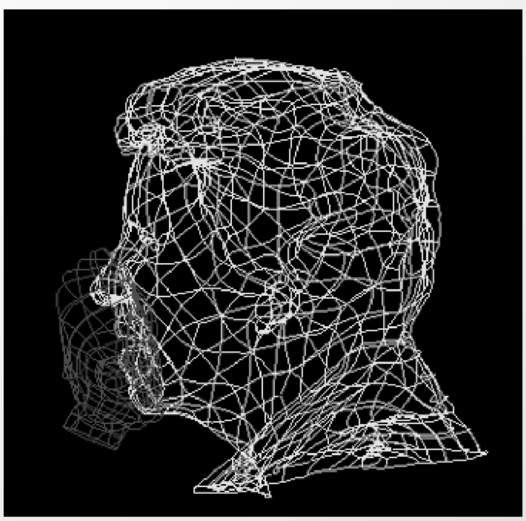
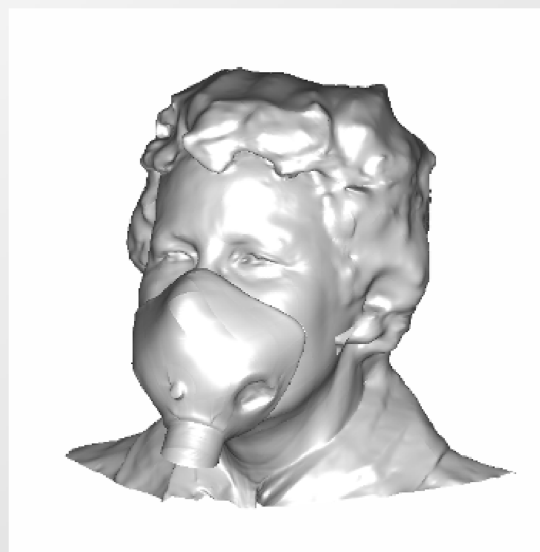
Prepare the Geometry







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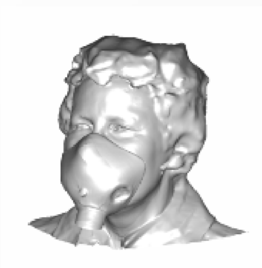
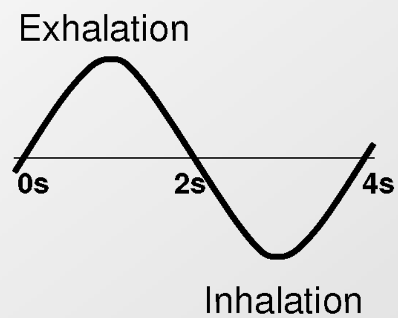
Interior Flow Model

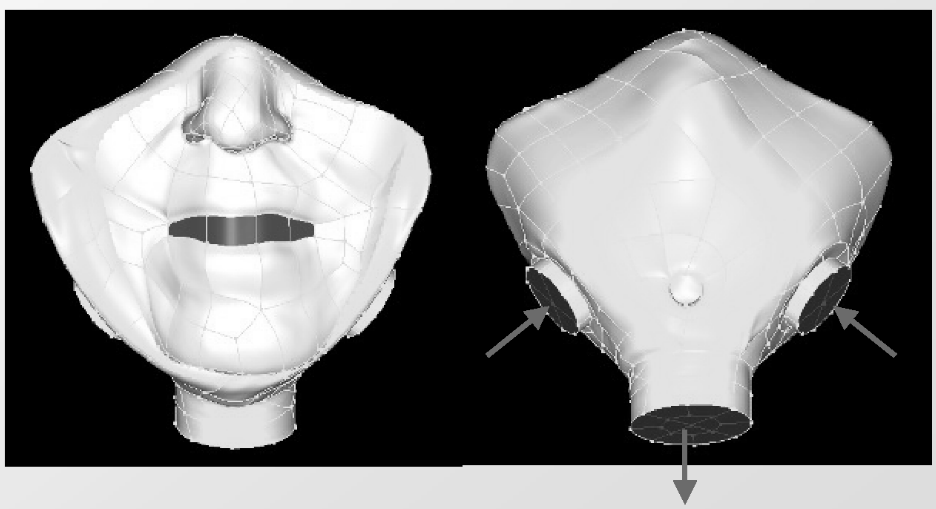


Breathing (at rest):

$V_T = 0.5$ L

f = 15 breaths/min





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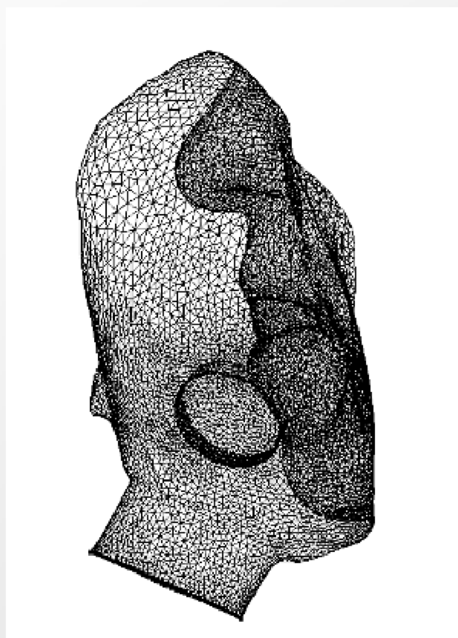
Mesh – Refined where needed



Mesh boundaries first, then interior
→ 350,000 cells

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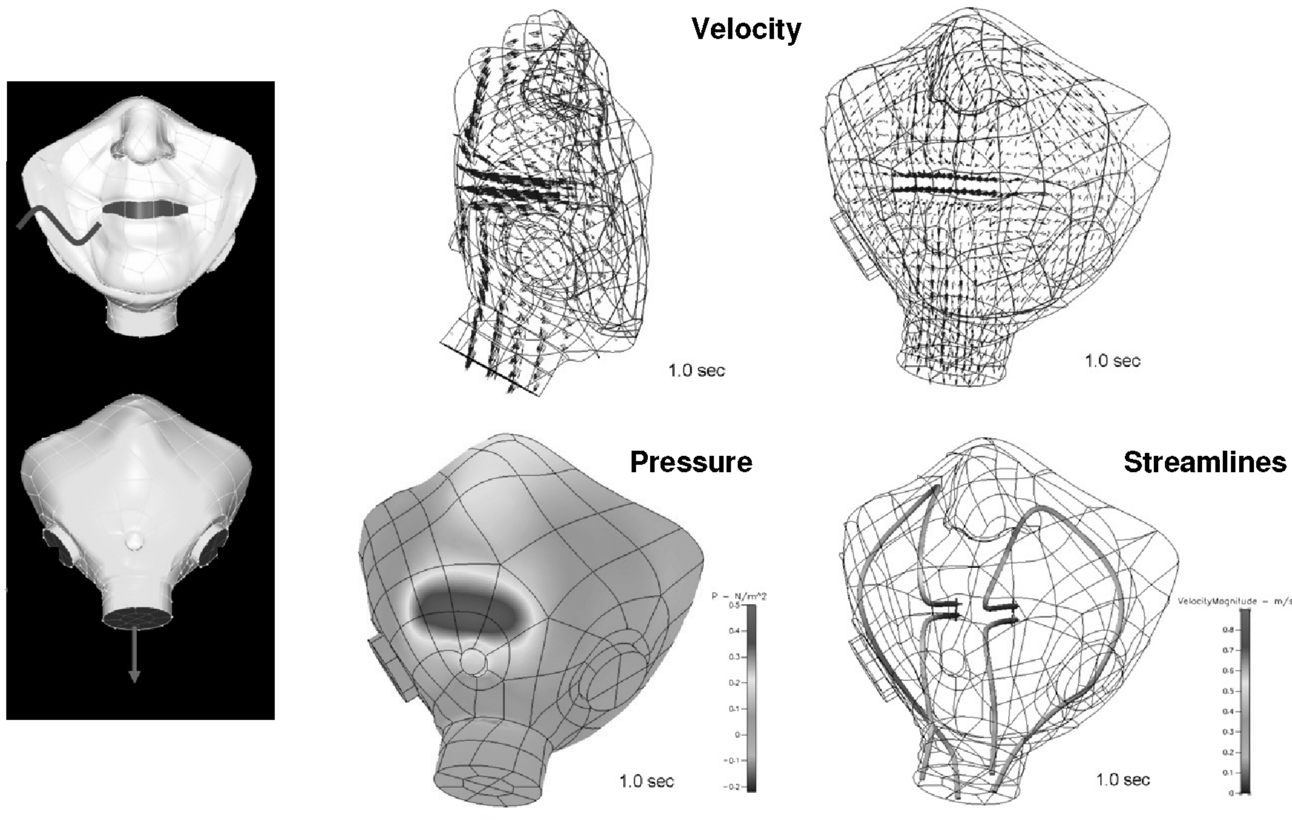
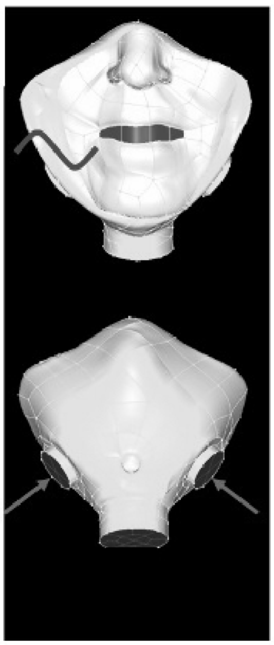
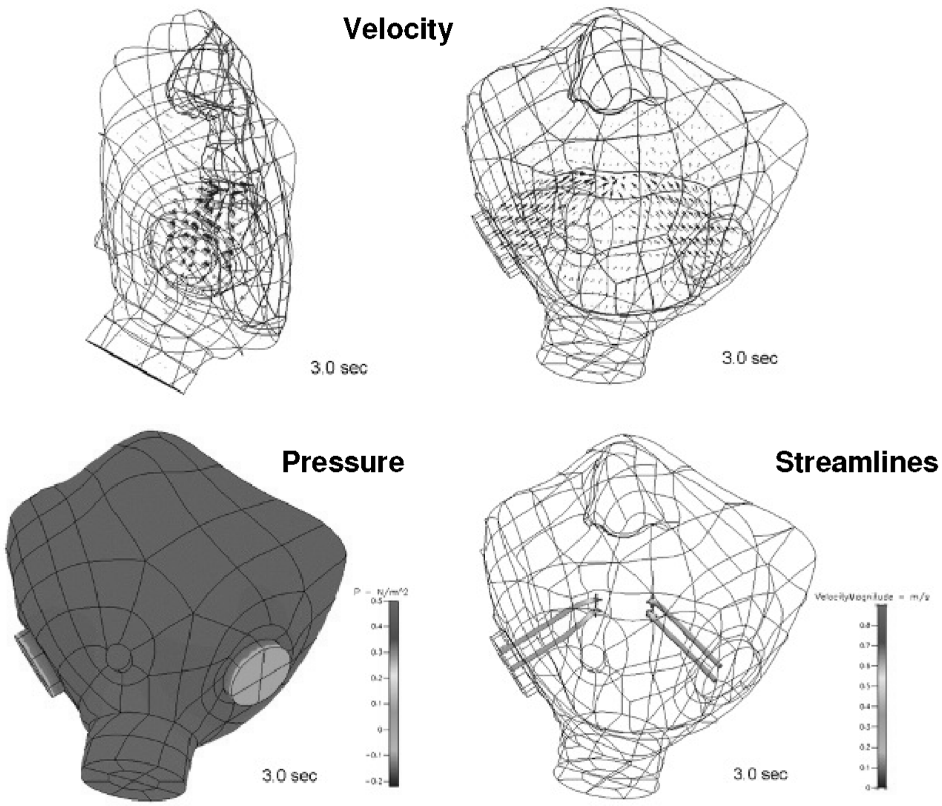
Gas Flow within Half Mask - Exhalation



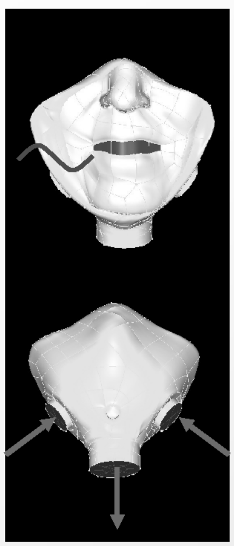
Gas Flow within Half Mask - Inhalation

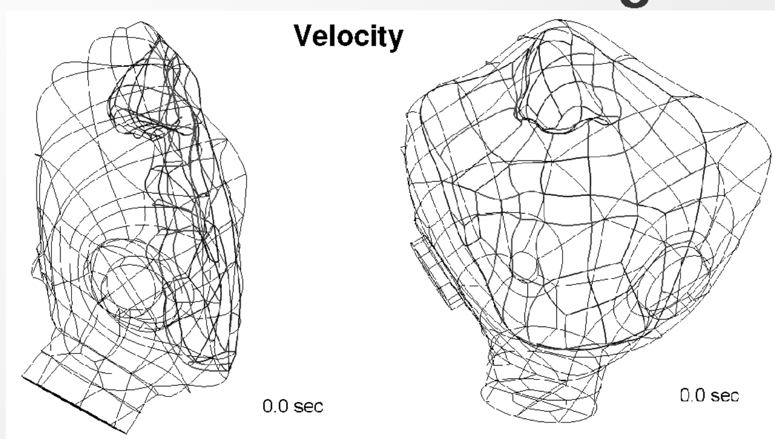


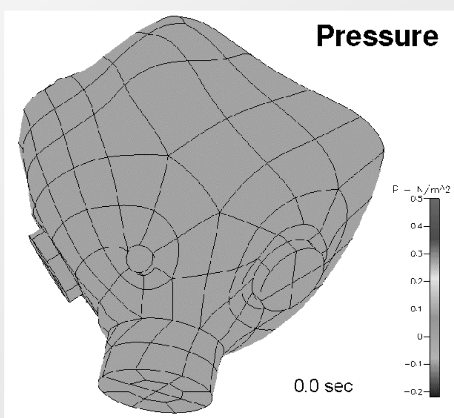


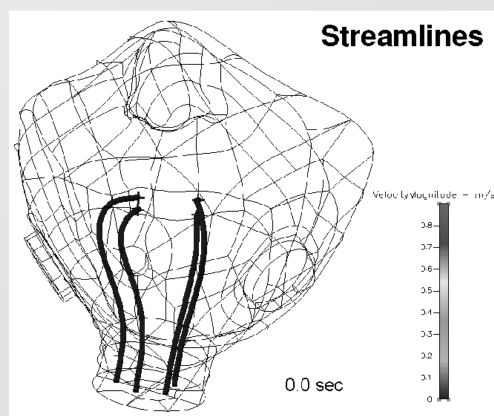
Gas Flow for Normal Breathing

V_T = 0.5 L
f = 15 breaths/min

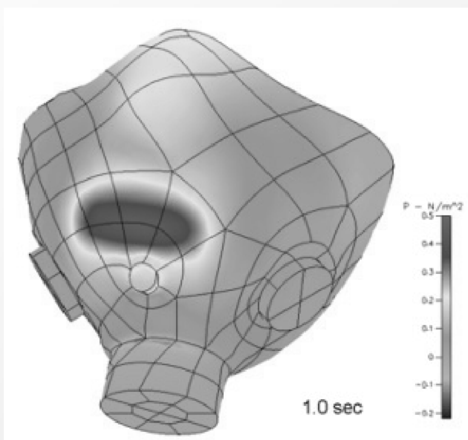
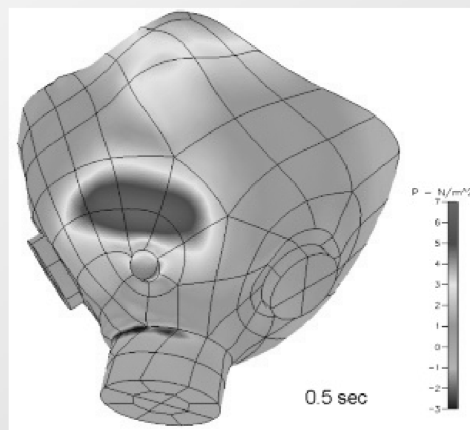








Comparison of Pressures

Normal Breathing	Under Work Load
	

Normal Breathing

V_T = 0.5 L
f = 15 breaths/min
P range ~ -0.2 to +0.5 Pa

Under Work Load

V_T = 1 L
f = 30 breaths/min
P range ~ -3 to +7 Pa

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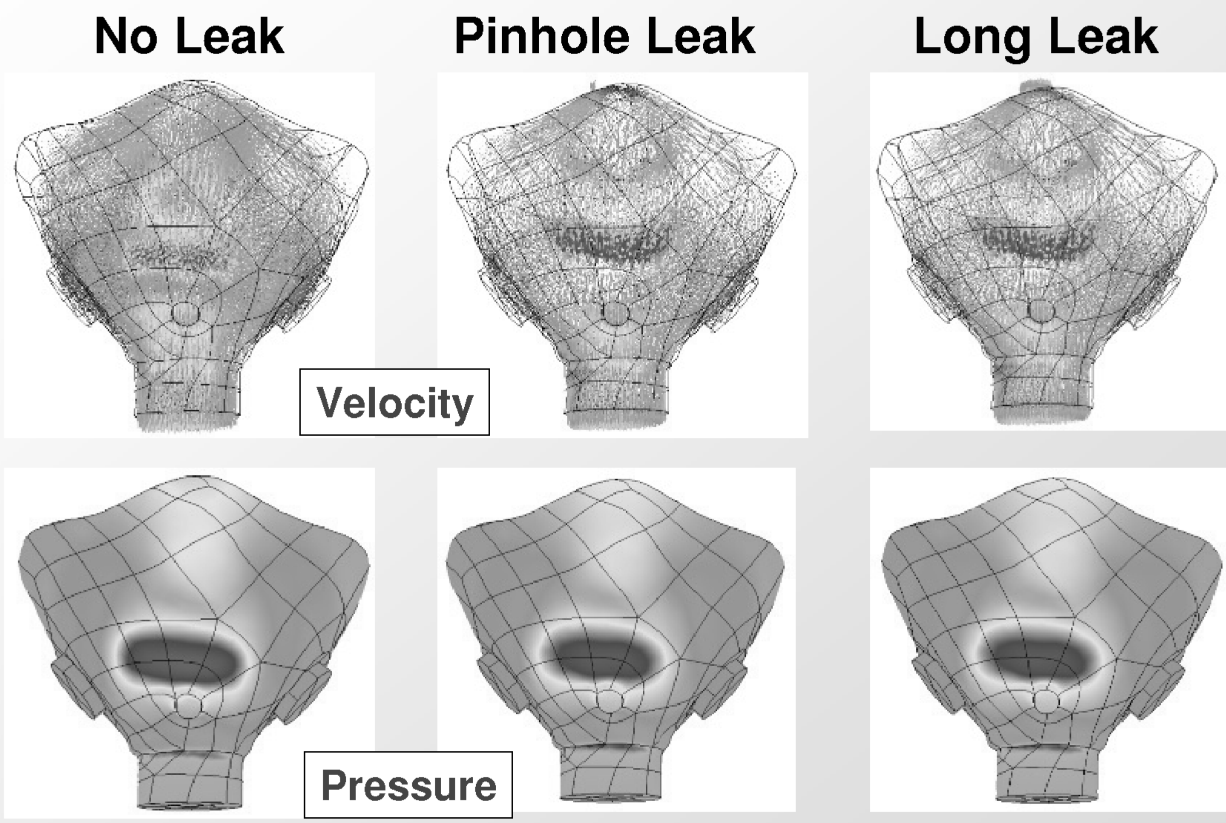
Comparison of Leaks



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