Development of an Oxygen-Conserving Mask for Pediatric Patients in Low-Resource Settings

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Abstract

INTRODUCTION:
Worldwide, the leading cause of mortality in children is acute respiratory infection, primarily associated with pneumonia. One of the essential tools used to treat life-threatening hypoxemia due to pneumonia is the appropriate use of supplemental oxygen. While oxygen therapy is essential for many aspects of case management in hospitals and large clinics, many such health facilities have no access to oxygen supplies, or are unable to maintain adequate supplies to meet requirements. The result is often avoidable death. To address this challenge, engineers at Global Good have developed oxygen conserving masks for pediatric patients that can significantly reduce the strain on oxygen supply logistics for low resource hospitals and clinics.

USE OF COMSOL MULTIPHYSICS:
The main requirements for the oxygen conserving mask was that it had to simultaneously provide sufficient oxygen savings for pediatric patients over a multi-year age range, while not increasing CO2 concentrations above a specified level. Achieving these requirements over an age range where physiological changes are significant required the development of patient models. These models had to be able to efficiently cover large parameter spaces with moderate levels of accuracy, and dive in to specific areas of that parameter space with a high level of accuracy. These requirements lead to the development of a one-dimensional model for examining large parameter spaces of both patient physiology and mask design, and a detailed three-dimensional model for examining performance of specific mask designs. The 1D model used the Transport of Concentrated Species module, and the 3D model coupled Transport of Concentrated Species with the Laminar Flow module. Both models included ODEs for simulating the concentration of O2, CO2 and N2 in the lungs.

RESULTS:
1D Patient and Mask Model
The validation of the 1D model showed close agreement with experimental when exhalation was rapid, and required tuning parameters when exhalation profiles lead to external flows that did not sufficiently jettison exhaled gases away from the mouth. The validated model was used to explore a large physiological parameter space that included child ages from 6 months up to 5 years, providing data for informing mask size selection that would enable meeting both O2 savings and CO2 retention requirements for the wearer.

3D Patient and Mask Model
The validation of the 3D model matched experimental measurements with a high degree of accuracy under all tested conditions. After validation, the 3D model was used to explore opportunities for improving O2 savings and reducing CO2 retention. The model identified localized regions of high CO2 within different mask design iterations, and guided experiments for verifying approaches for removing these high CO2 regions. Additionally, the model clarified the main mechanisms by which the mask was improving O2 savings under different respiratory waveforms.

CONCLUSION:
• The 1D model was sufficient for describing O2 and CO2 transport within simulated pediatric patients under most respiratory waveforms explored, but lost predictability without tuning parameters when the respiratory waveforms lead to significant temporal variability in the gas concentrations just outside of the model boundaries.
• The 3D model matched experimental system behaviors under all ranges explored, and enabled for a detailed look into how mask design influenced CO2 retention and O2 savings.

Figures used in the abstract

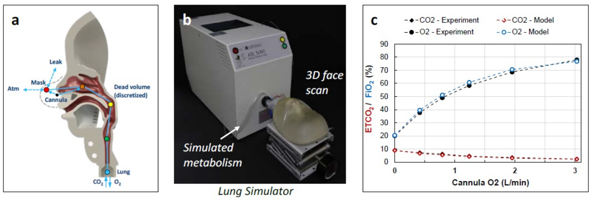

Figure 1: (a) Mapping of detailed pediatric physiology into the simplified 1D model domain. (b) Experimental setup for simulating pediatric respiration; setup included accurate gas inputs (N2, O2, CO2) realistic respiratory waveforms. (c) Model validation results for the 1D model with rapid exhalation.

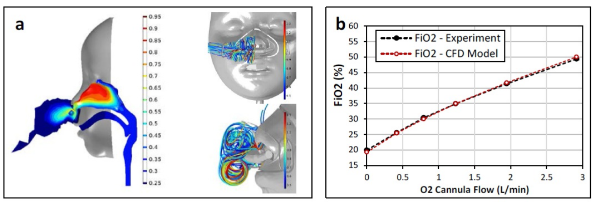

Figure 2: (a) Images from the 3D simulation showing O2 concentrations during exhalantion (left), and recirculation vortices during exhalation colored by residence time (right). (b) Model validation results for the CFD model.