How does gravity affect our lungs?

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Introduction

The lung has a very specific and complex structure, able to stretch and expand in such a way that is essential to the process of breathing. With millions of alveoli each expanding to allow air to flow through (1). But this malleable form means that the lung can be affected by many external forces, including the most fundamental force on Earth: gravity (2). But how exactly does gravity impact the function of our lungs?

Covid-19

We know that something as simple as the position in which a patient is laying can have a significant effect on their health. The Covid pandemic saw a considerable improvement in oxygenation when a patient was turned onto their front (prone) (3), and it is believed that a big part of this is their orientation against gravity.

AIM: To mathematically model the deformation of alveoli due to gravity in different positions.

Methods

Using solid mechanics, I created two models representing different shapes as an analogy of the lung. Shape is adjusted for body position with the model always being calculated parallel to gravity.

Alveolar units were initially spread evenly across the vertical line, and then gravity was applied to calculate how far each alveolus moved and stretched from its original position.

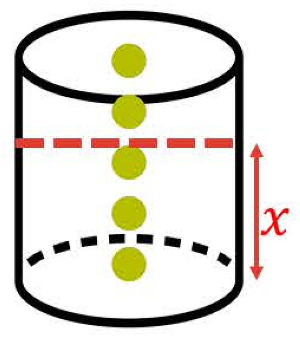
From the Bar Equation:

$$\frac{d}{dx}\left(EA\frac{du}{dx}\right) + pgA = 0$$

where
E = Young's modulus
A = Cross-sectional area
$u(x)$ = deformation at x
p = tissue density
g = gravitational force

To fix the top and bottom of the lung we implement the boundary conditions:
$u(0) = 0,\ u(L) = 0$
where L is the vertical distance up the lung

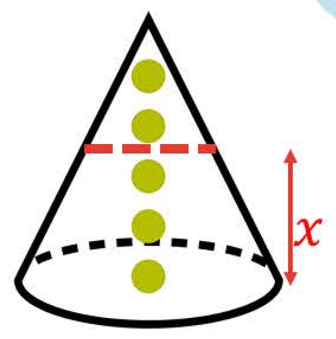
Cylindrical Model:



A is constant across x and so $u(x)$ becomes:

$$u(x) = -\frac{pgx^2}{2E} + \frac{pgLx}{2E}$$

Conical Model:



A varies across x according to

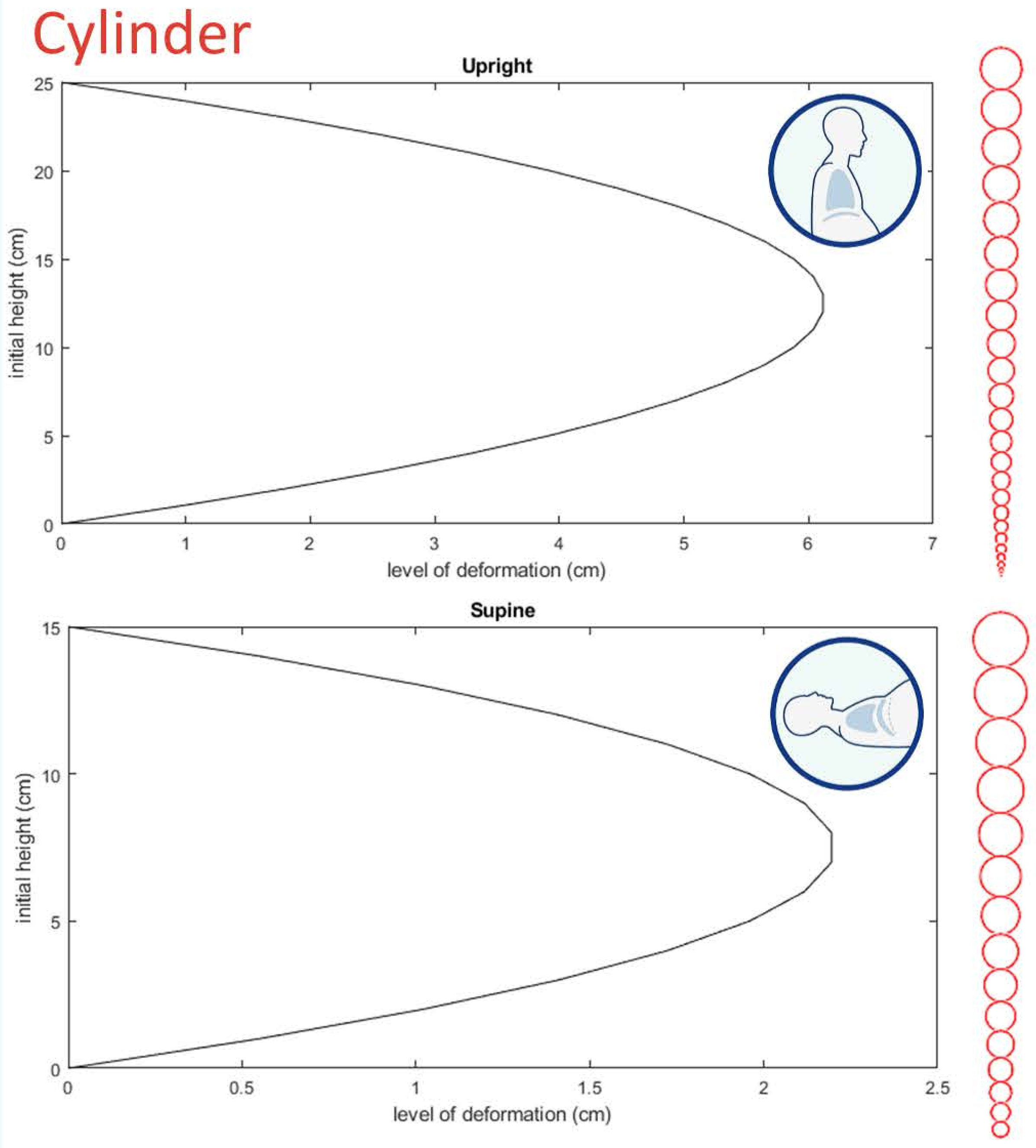
$$A(x) = \pi\left(\frac{rx}{L}\right)^2$$

With r being the radius of the cone's base. Now $u(x)$ becomes:

$$u(x) = \frac{pg(x-1)(L^2+L-x^2-x)}{6Ex}$$

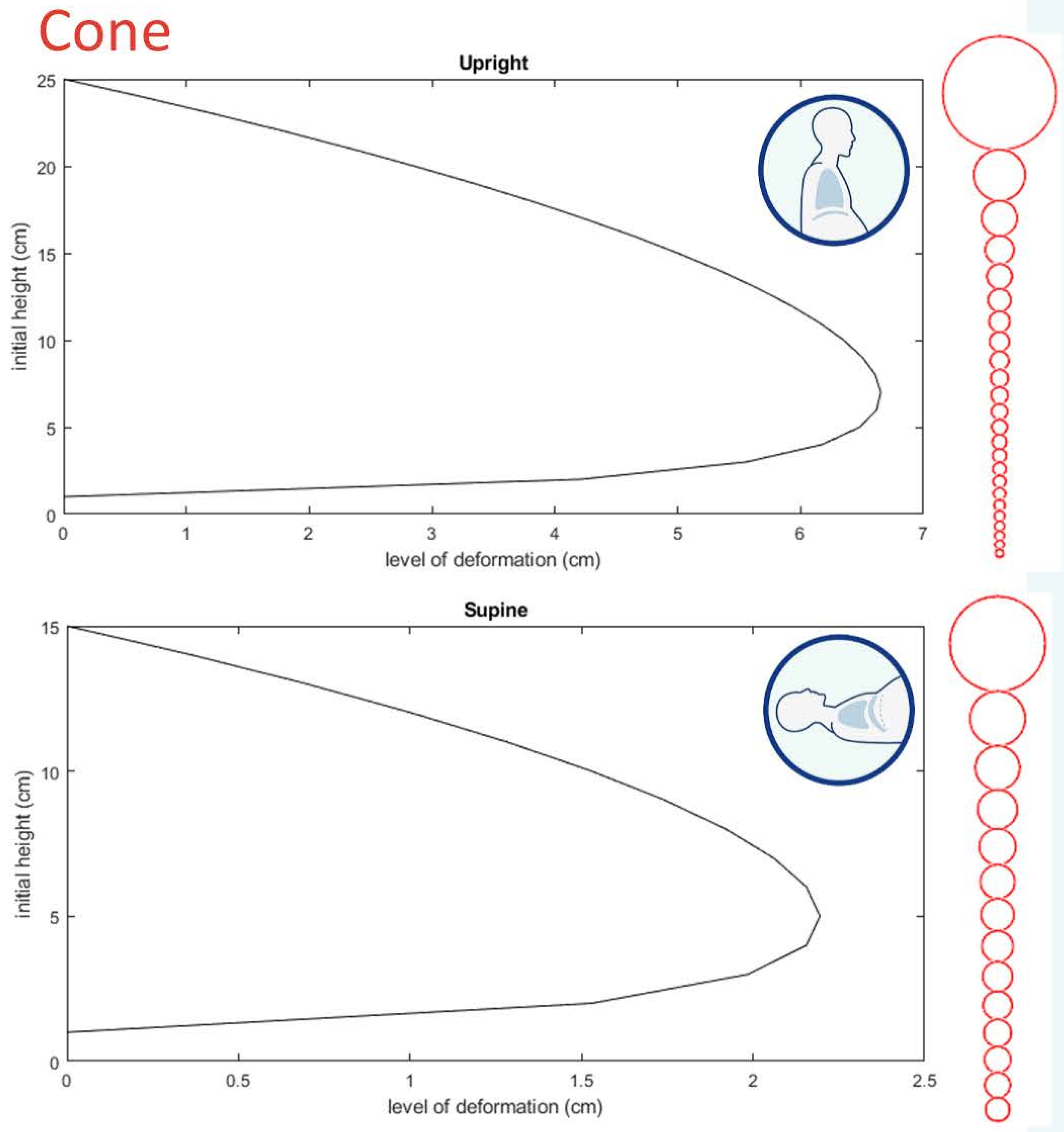
Results

Cylinder



- The alveoli at the top of the lung are larger than those at the bottom, regardless of position or model shape. This is referred to as the slinky effect (4).
- The uniform model, shows a symmetrical level of deformation between the top and bottom of the lung, whereas the cone model shows much greater deformation towards the bottom of the lung.
- In both models, alveoli are more uniform when in the supine position and overall deformation is decreased. This means that both ventilation and perfusion are more consistent across the lung.

Cone



Ventilation levels are relative to the size of the alveolus, with smaller alveoli being able to stretch further and allow more air to flow through. This means ventilation is higher in the dependent part of the lung.
Similarly, due to the increased number of alveoli, perfusion is also higher in the dependent region of the lung (5).

Conclusion

Gravity has a significant impact on the structure and performance of the lungs, meaning changes in body position can result in anticipated improvement in patient condition. By creating a model which incorporates all of the factors associated with positioning, we can explore the implications of different maneuvers and the expected outcome for the patient.

Further work

- Using this deformation model to accurately estimate the perfusion and ventilation in each area of the lung.
- Incorporating external pressures such as the heart and abdominal contents.
- Extending the model to assess the implications of different lung conditions, updating to make it as specific to a patient's condition as possible.
- This model will be integrated into the existing ventilation model chosen by CHIMERA.

References

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