CPR: Are You Saving People the Right Way?

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Executive Summary

With the recent decision of the American Heart Association to endorse CCR training over CPR training, we decided to investigate claims of efficiency and compare the two methods. CPR and CCR are two related techniques used to help oxygenate a person who has experienced cardiac arrest. The significant difference between them is that CPR involves rescue breaths, which re-oxygenate the lungs but stop compressions which in turn, stop blood flow, while CCR consists of only chest compressions. There is much debate as to which method is more effective at delivering oxygen to the bloodstream. We used COMSOL to model and study CPR and CCR and determine which method induces a greater oxygen flux through the alveolus and into the capillaries. CPR was modeled with rescue breaths and no convective flow near the end of the cycle, while CCR involved constant convective flow past the alveolus-capillary boundary. We found that while CPR creates a somewhat higher oxygen concentration in the blood, its oxygen flux drops to zero during rescue breaths. CCR delivers a consistently larger oxygen flux to the lungs since it never drops to zero. When the overall oxygen concentrations in the bloodstream over time are compared between the two methods, it is clear that CCR has the advantage over CPR. Therefore, we conclude that CCR is a more effective method of delivering oxygen to a person who has experienced cardiac arrest.

Introduction

Cardiopulmonary Resuscitation (CPR) is a technique used around the world to help save the lives of people who have experienced sudden cardiac arrest. It is designed to prevent brain and tissue damage due to a lack of blood circulation and to prolong a person's chance of survival until emergency personnel arrives.[1] It has been established as one of the most effective interventions for such medical crises and for increasing the chances of the return of spontaneous circulation. It was developed over five decades ago and the procedure remains generally unchanged to this day. The technique uses a cycle of thirty compressions of the heart followed by two "rescue breaths". Though the compression-breath method has been in use for quite some time, recently there has been a new recommendation for CPR, called cardiocerebral resuscitation (CCR) that involves only compressions and no rescue breaths.

When cardiac arrest occurs, the heart stops pumping blood and so, oxygen delivery is essentially halted. This would not be a problem for most tissue in the body because oxygen reserves and metabolic requirements allow them to survive even with oxygen deprivation for hours. However, for the heart and the brain, survival may be as short as only a few minutes. Brain damage occurs in varying time periods, depending on the person and circumstances, but is generally in the range of five to fifteen minutes. Also, to achieve the return of spontaneous circulation (ROSC) through subsequent ALS (advanced life support) procedures, such as an AED (Automated External Defibrillation), the ischemic myocardium tissue must have some level of oxygen replenishment; there must be some level of previous oxygen transport in the blood which can be provided by CPR. [3]

The attraction of CCR is two-fold. The first lies in the fact that rescue breaths, though a simple concept, can go disastrously wrong if performed incorrectly; this mostly concerns laypersons, people who have no medical training but have taken a CPR class. If the airway is not opened correctly, a layperson could breathe into the stomach, induce vomiting and cause a new host of problems; or their

breaths might not go anywhere if both the trachea and esophagus remain closed. If this occurs, the layperson may try to fix their technique in the middle of performing CPR and stop performing chest compressions.[2]This is where the second advantage presents itself. An interruption to chest compressions will cause a decrease in blood pressure and blood flow as well as decrease the oxygen perfusion in the heart and brain, all factors that drastically diminish the chances of ROSC.[4] By eliminating rescue breaths and therefore, any interruption of chest compressions, the chances of ROSC should increase. However, the problem with CCR is the question regarding whether there is enough oxygen present in the lungs to make CCR a viable and effective alternative to the traditional CPR procedure. Without rescue breathes, fresh air is not delivered to the lungs and so the oxygen in the alveoli is not replenished. The oxygen in the alveoli therefore decreases with each passing minute of CCR; there may not be enough to sustain life past a certain amount of time.

An important recent development regarding this matter is the change in policy of the American Heart Association. They have recently decided to endorse CCR training over CPR training. American Red Cross, on the other hand, has continued to endorse CPR training. This makes our experiment doubly important because the American Heart Association and the American Red Cross are the two largest providers of CPR/CCR training classes and most, if not all of those who are trained to perform CPR, including paramedics and EMTs, have been trained through one of these agencies. Therefore, this apparent disconnect between policies is a potential future problem.

Many studies have been done on this subject.[4,6-8] One such study concludes that rescue breaths are not necessary in performing effective CPR. The researchers simulated a situation in which a single rescuer bystander performs an intervention on a pig in which cardiac arrest had been induced. After two minutes of untreated cardiac arrest and twelve minutes of bystander help, ALS intervention began, with administration of AED and epinephrine as though a paramedic had arrived. Forty three pigs were treated with CCR, CPR or no CPR. The concentration of oxygen and carbon dioxide as well as the pH in the blood was monitored. Five out of fourteen CCR, three out of fifteen CPR, and one out of fourteen no CPR pigs survived past twenty four hours. The myocardial oxygen delivery and consumption was the same for both CCR and CPR pigs.[8]

However, another study concluded that CCR was not effective in inducing ROSC in cardiac arrest victims. In this study, researchers compared four different compression/ventilation ratios (30:2, 100:5, 100:2, compression-only) on 32 pigs in which cardiac arrest had been induced. After three minutes of untreated cardiac arrest and ten minutes of one type of intervention, ALS intervention began with administration of an AED and adrenaline. ROSC was achieved in four out of eight 30:2, five out of eight 100:5, two out of eight 100:2 and zero out of eight compression-only pigs. The oxygen concentration in the blood was measured. There was a decrease in peripheral arterial oxygenation in the 100:5 and compression-only pigs that possibly decreased the chances of ROSC. The concentration was about the same for 30:2 and 100:5 compression rate pigs.[4]

With so many differing opinions regarding this matter and the research reinforcing each position, it is certainly hard to make a conclusion about such an important procedure. Therefore, we will investigate for ourselves and model both types of CPR in COMSOL to determine which method is more effective in preserving life.

Design Objectives

We plan to evaluate the effectiveness of traditional CPR (CPR #1) whereby the rescuer gives a cycle consisting of 30 compressions followed by 2 "rescue breathes", in comparison to an alternative proposal where the cycle consists of only compressions and no "rescue breathes" (CPR #2/ CCR). We will then determine whether claims that the second method saves more lives are true or not; this will be decided by whether the oxygen levels in the blood is enough to sustain brain activity, and whether it is different from that of traditional CPR.

- To model oxygen intake in the lungs with rescue breaths and with no rescue breathes
- To determine how much oxygen is being delivered to the body
  - To find the amount of oxygen that is diffusing from an alveolus in the lungs into a capillary covering that alveolus in two different models (model with 2 "rescue breathes" and model with no "rescue breathes")
- To determine the blood flow resulting from chest compressions

Simple Solution

For our simple solution we considered only the blood vessel area with a boundary shared with the alveolar wall and a constant oxygen concentration at boundary 1. No blood is flowing.

Schematic:

The diagram of our model.

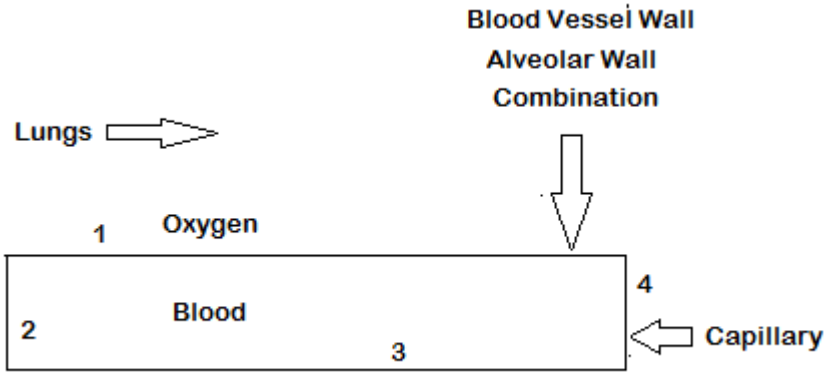

Figure 1. Schematic drawing of a simplified version of the capillary/alveoli interaction for the simple solution

Assumptions:

The assumptions made to simplify a complex model into the one seen above.

1. There is no air flow in the lungs.
2. There is no blood flow in the capillary.

3. The wall of the blood vessel and the wall of the alveoli are considered be thin enough to combine into one entity and, thus have the same diffusion constant.
4. There is no degradation of oxygen in the lungs or the capillary.
5. The flux across the wall is constant.
6. The blood vessel is insulated at the other side (boundary 3) because there is no contact with alveoli on that side.
7. The capillary is insulated at both ends (boundaries 2 and 4) because the capillary is very long and we are looking at only a small section of the alveoli-capillary contact.

Governing Equation:

These are our governing equations for our model. We started with the general equation for mass diffusion and eliminated the generation term, since we assumed that oxygen is neither generated nor degraded; and then eliminated the convection term, since we assumed no blood flow. This leaves us with the transient and diffusive terms.

$$\frac{\partial c_A}{\partial t} + \cancel{u\frac{\partial c_A}{\partial x}} = D_{AB}\frac{\partial^2 c_A}{\partial x^2} + \cancel{r_A}$$

$$\frac{\partial c_A}{\partial t} = D_{AB}\frac{\partial^2 c_A}{\partial x^2}$$

Boundary Conditions:

Flux will be zero at the boundaries 2, 3 and 4. Flux at boundary 1 is a given value.

Initial Conditions:

The concentration of oxygen in the blood is initially zero. The concentration of oxygen in the lungs is a given value.

Limitations:

With a simplified model, the conclusion made will not be as realistic as one made with a more complex model with less assumptions.

1. This model does not account for the convection in the lungs when a "rescue breath" is issued as part of CPR.
2. This model does not account for the blood flow that the compressions of CPR induce.
3. The blood vessel wall and the capillary wall do not have the same diffusion constant and the combination of the two will cause undesirable inaccuracies in the data.

Mesh

Scenario for Mesh and Complete Solution:

A person has just had a heart attack. We will be assuming that the person has an asystolic heart rhythm (the heart has stopped beating). Blood will not be flowing though the blood vessels and thus will be stagnant. The person took a full breath of air before he collapsed and his airway closed (preventing any transfer of air between the lungs and the atmosphere) so the oxygen concentration in his lungs is the same as the concentration of oxygen in the air.

The original mesh is included in the appendix. We then performed a mesh convergence analysis on the problem using the average oxygen concentration in the blood vessel, and obtained the final graph shown below.

Mesh Convergence:

This is a table of our mesh convergence element values and the oxygen concentration values that resulted from the change.

Table 1. Number of Elements in the mesh versus the oxygen concentration in the blood vessel for the purposes of mesh convergence

Number of Elements	Total Concentration of Oxygen in blood vessel (mol/m)
2800	2.479608E-08
11200	2.479673E-08
25200	2.479733E-08
36400	2.479725E-08
44800	2.479735E-08

Next is a graph of these values, showing where the solution converges and thus which mesh element is sufficient for our purposes.

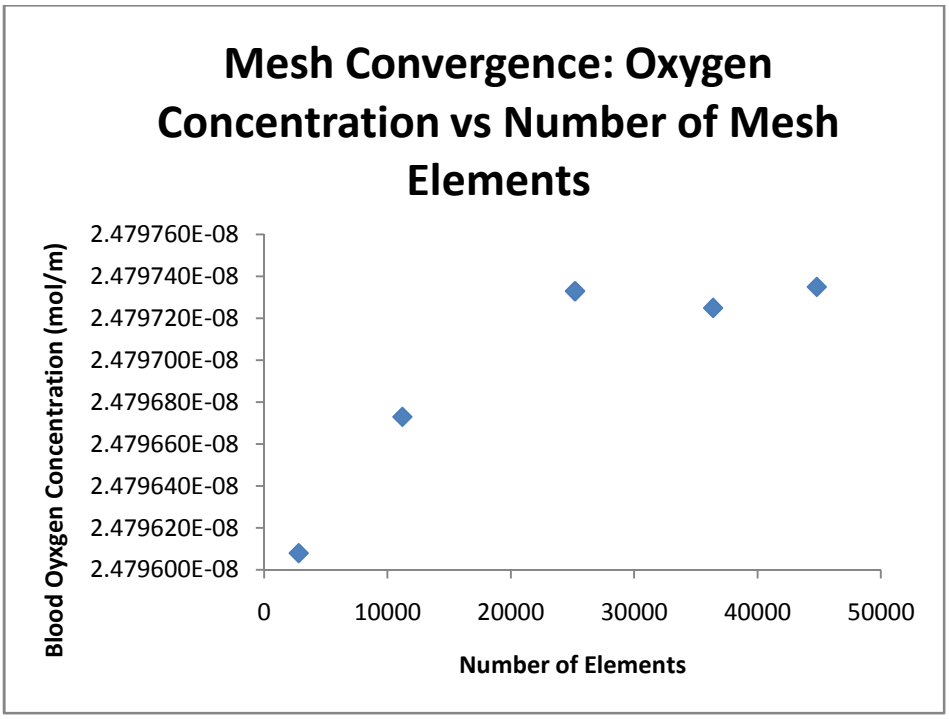

Figure 2. Plot of the oxygen concentration in the blood vessel against the number of elements in the mesh for the mesh convergence

Overall, the mesh converges to a final oxygen concentration around roughly 40000 to 50000 elements. There is a slight anomaly in the data at 37000 elements, however, since the rest of the data follows the same general pattern and the anomaly is so small, it is not considered significant to the problem. The number of mesh elements that was used for the final solution was 45000.

Complete Solution

This is the schematic for our complete solution, with minimum assumptions made. Oxygen diffuses through boundary 5 of the alveolus (top area) and then crosses into the capillary (bottom area). Blood is flowing from boundary 1 into boundary 6, producing convection.

Schematic:

The diagram of our final model.

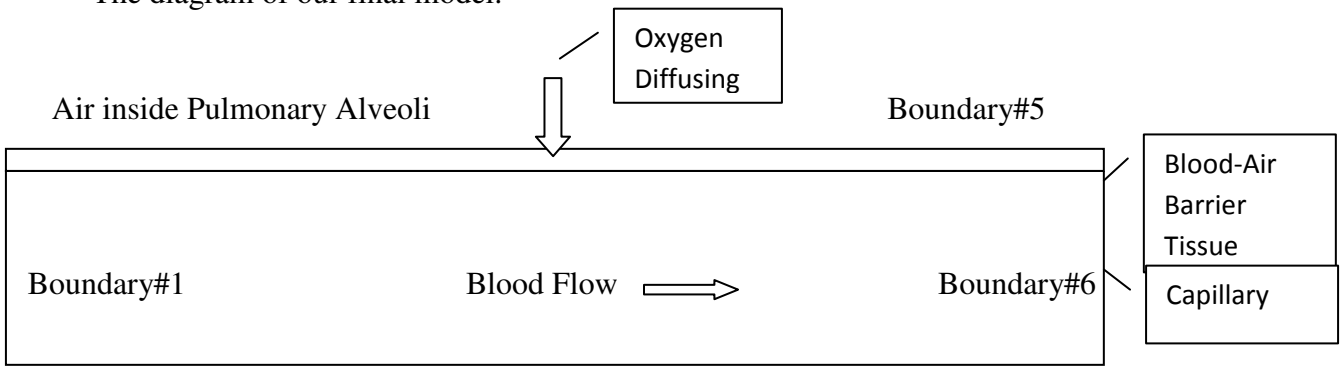

Figure 3. Schematic of the capillary/alveoli interaction for the complete solution.

Assumptions:

These are the assumptions made to simplify the model and make it more manageable and solvable.

1. Blood and body temperature will stay the same – reasonable because the body is such a large mass the temperature will not change much from the initial 37 ^{o}C.
2. Person took a full breath before collapsing. The airway is closed so no air escapes or enters.
    a. Oxygen concentration in lungs is same as oxygen concentration in air.
3. The oxygen flux from the air to pulmonary alveoli wall is constant.
4. The oxygen flux from the pulmonary alveoli wall to the capillary wall is constant.
5. The oxygen flux from the capillary wall to the blood is constant.

Dimensions:

We used the following dimensions for our model.

Table 2. The dimensions of the blood vessel and wall that is to be modeled in COMSOL.

	Width (um)	Height (um)
Blood-Air Barrier Tissue	300	1
Capillary	300	15

Governing Equations:

For our complete solution we once again started with the general equation for mass diffusion. However, this time the only term we remove is the generation term. Since we now assume blood flow, the convection term remains, and we introduce a second governing equation for fluid flow in the capillary. Since air is stagnant, this equation does not apply in the alveolar area.

$$\frac{\partial c_{O_2}}{\partial t} + \left(v_x \frac{\partial c_{O_2}}{\partial x} + v_y \frac{\partial c_{O_2}}{\partial y}\right) = D_{O_2 B}\left(\frac{\partial^2 c_{O_2}}{\partial x^2} + \frac{\partial^2 c_{O_2}}{\partial y^2}\right) \rightarrow \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(u\rho) = 0 \text{ (Mass Transfer)}$$

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x}\right) = \rho g_x + \mu\frac{\partial^2 u}{\partial x^2} - \frac{\partial P}{\partial x} \text{ (Fluid Flow)}$$

Boundary Conditions:

These are the boundary conditions used for our model.

At Boundary#1: [Oxygen]=5.50 mol/(m^3) (Assume to be the concentration of oxygen in de-oxygenated blood)

At Boundary#5: [Oxygen]=8.25mol/(m^3) (Assume to be the concentration of oxygen in air)

At Boundary#6: Convective flux determined by COMSOL

Initial Conditions:

These are the initial conditions for our model.

Capillary: [Oxygen]=5.50 mol/(m^3) (Constant for simplified solution, but is function for complex solution)

Alveolus: [Oxygen]=8.25mol/(m^3)

Material Properties and Constants

These are the constants that we found from literature that we used in our model.

Diffusion of oxygen through the alveolus: 1.1e-12m^2/s

Diffusion of oxygen through the capillary: 3.24e-9m^2/m·s

Blood Velocity through the capillary: 4.70e-6m/s

<u>Post-Processing Analysis</u>

Once again, the average concentration of oxygen in the blood vessel is modeled at various points within the capillary and it can be seen that as one gets closer to the surface of the capillary and thus closer to the vessel-alveolus boundary, the concentration of oxygen increases. The sharp dip in oxygen concentration present in our previous graph has been reduced significantly; while the oxygen concentration still decreases initially, it is not as drastic, hinting that the original spike in oxygen concentration was likely caused by an insufficient mesh.

The concentration profiles for both the initial and final meshes are very similar, with oxygen concentration slowly increasing in the capillary as the blood flows past the oxygen-rich alveolus; the

final profile does not change significantly in terms of value or general appearance. The concentration profiles are attached in the Appendix.

There is also a graph comparing the flux of oxygen into the blood between CPR and CCR (figure 7,8). It can be seen that the two have almost identical oxygen flux until the final seconds of the second, at which point the CPR oxygen flux drops to zero. This seems reasonable, since during the final stages of the model rescue breaths are performed; the flux of oxygen into the blood would then cease since no compressions are occurring.

We then compared the concentration of oxygen in the blood during various points in CPR and CCR (Figure 12.). It can be seen that concentrations of oxygen are very similar for both methods at first. In the beginning, CPR experiences a minor spike; both then follow the same curve, where the oxygen concentration spikes suddenly and then slowly decreases. However, CPR then experiences a second spike near the end of the middle and end time runs; CCR continues to steadily decrease.

Accuracy Analysis

We performed an accuracy analysis for our final oxygen concentration profile by comparing the values we obtained through COMSOL with those calculated in literature. We found a small paper where the blood concentration in the cerebral area of the brain was calculated to be 5.175mM[5]. The values we calculated, however, are somewhat higher, at 7.15mM at the maximum and 6.90mM at the minimum for CPR, and 6.909mM and 6.900mM for CCR. This is likely because the blood concentration in the brain is going to be much lower than that coming directly from the alveolus, since the oxygen is delivered to all of the body and thus only a fraction of itgoes directly to the brain. Thus, the values we have obtained seem fairly reasonable thus far.

Sensitivity Analysis

We performed a sensitivity analysis on the blood velocity and oxygen diffusivity of our model, since these two values will greatly impact how well oxygen diffuses into the blood during CPR. Sensitivity towards either of these two variables may greatly affect our model and thus require us to obtain the most accurate data available for these two variables.

This is a graph of our sensitivity analysis on blood velocity as it affects our solution. We multiplied the original velocity by constant values and observed the change in total flux.

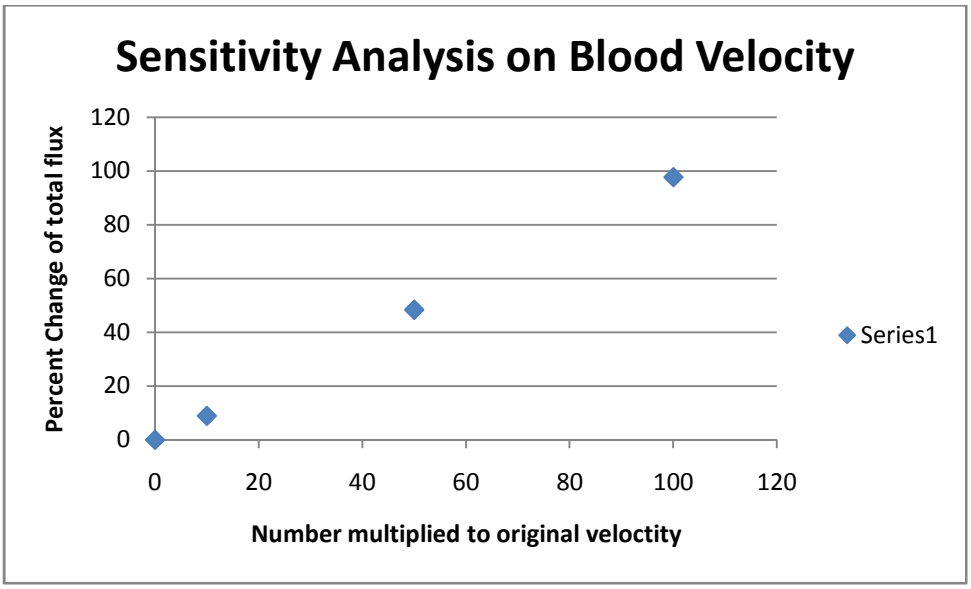

Figure 5. Sensitivity analysis of our model in regards to blood velocity. The graph is distinctly linear and thus we can conclude that our model is very sensitive to blood velocity.

It can be seen that the relationship is linear, with the increase in velocity being almost perfectly matched by the same percent change in the flux. Thus, we can see that our model is very sensitive to blood velocity, and we should search for the more accurate values available for the blood velocity around the capillaries.

Next is a graph of our sensitivity analysis on oxygen diffusivity into the blood, generated using the same method for blood velocity above.

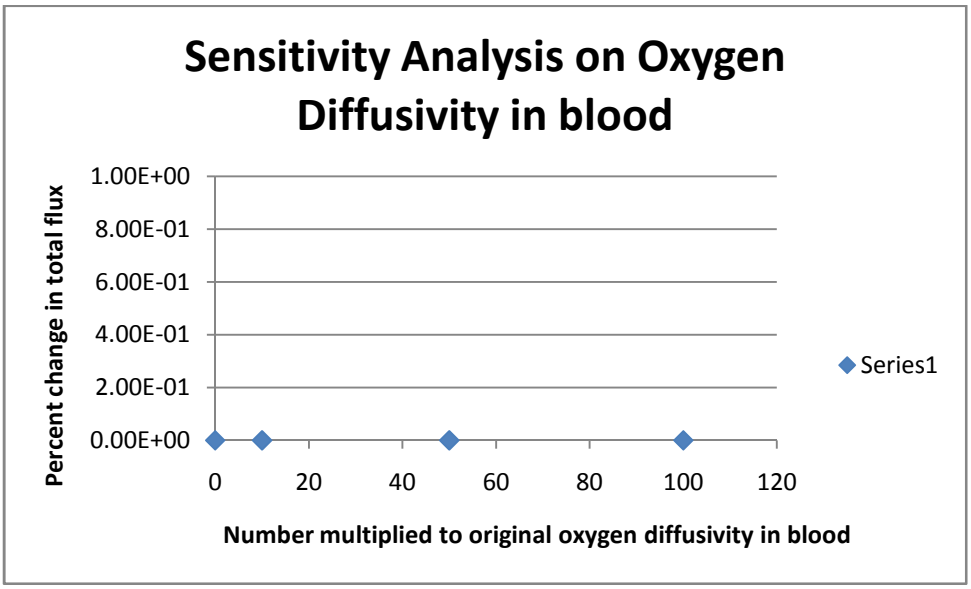

Figure 6. Sensitivity analysis for our model in regards to oxygen diffusivity. It can be seen that the final flux does not change with oxygen diffusivity and thus the model is not sensitive to this parameter.

Unlike blood velocity, the final oxygen flux values hardly change as the diffusivity of oxygen into the blood is changed.Our model then appears to be completely independent of the oxygen diffusivity.

Conclusion

We ran our model for two separate scenarios, CPR and CCR, and changed the appropriate settings for each. We obtained the below graphs for each of our solutions, showing the oxygen flux into the bloodstream as a function of time (one CPR cycle of thirty seconds):

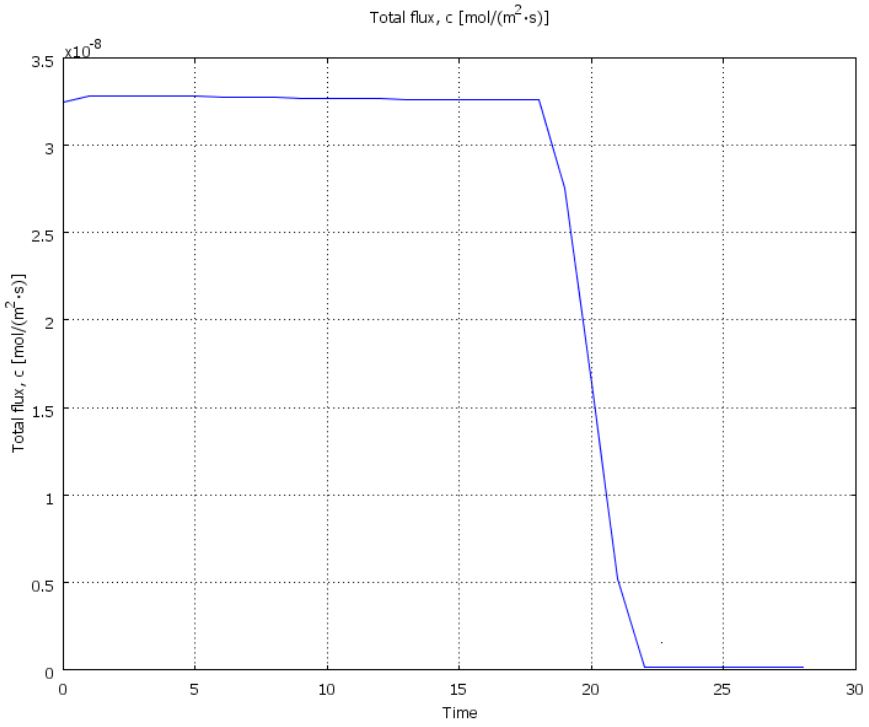

Figure 7. Flux versus time inside the capillary for CPR for our final solution. The flux stays relatively constant up until the rescue breaths are applied, at which point the flux drops rapidly to zero.

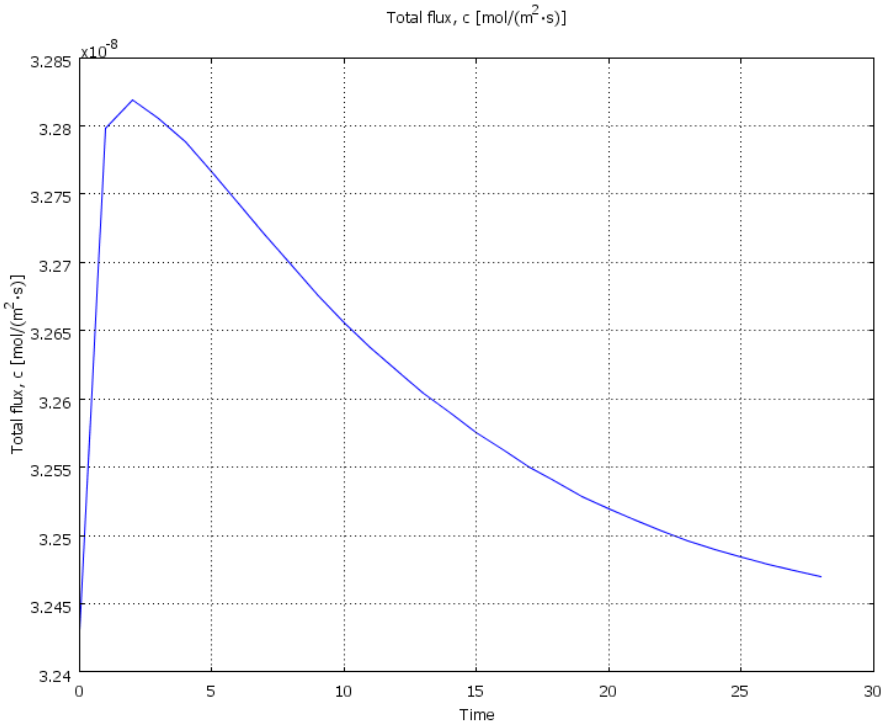

Figure 8. Flux versus time inside the capillary for CCR for our final solution. The flux reaches its maximum value early in the cycle and then slowly decays to a steady value. Note that the scale on this graph is different from that in Figure 7.

A very important thing to note about the two graphs is that the CPR graph's scale starts at zero flux but the CCR graphs starts at 3.24 mol/m^{3}s, which is roughly where the CPR graph has begun to peak.

The shapes of the two graphs are drastically different; the flux of oxygen into the blood in CPR drops to zero at the end of the cycle, while that of CCR decays to a constant value. This constant value is similar to the value recorded for CPR. Were this cycle repeated, one could expect that the flux of oxygen in CPR would once again rise to a steady value, and then drop; the flux in CCR would not change for repeated cycles, since the chest compressions would be not be stopped. This then implies that CCR is more effective at delivering oxygen to the blood, since the flux would not fluctuate to zero like in CPR.

We then obtained maximum and minimum values for CPR and CCR, which are as follows:

Table 3. Maximum and minimum oxygen concentration values obtained for CPR and CCR. There is a greater range in CPR, while CCR oxygen concentrations are constant.

	CPR	**CCR**
Max. O_2 Conc.	7.15mM	6.909 mM
Min. O_2 Conc.	6.90 mM	6.900 mM

Though it seems as though CPR provides more change in oxygen concentration in the bloodstream than CCR, and it does, we must take this finding in consideration with our findings regarding the oxygen flux. These concentration values only reflect a single cycle, which we have defined as 30 chest compressions and 2 rescue breathes (CPR) or 50 chest compressions (CCR). With the oxygen flux, we can see and predict future oxygen concentration trends and it shows that while CPR delivers burst of oxygen to brain and tissue, the CCR maintains a constant supply of oxygen and in the long run, this supply of oxygen will prove to be larger than that of the supply maintained by CPR.

Our sensitivity analysis provides further proof that CCR is more effective than CPR. Our model is extremely sensitive to blood velocity; thus, if the blood is not moving, then the flux of oxygen into the blood will decrease drastically. Therefore, during rescue breaths, the flux of oxygen will drop significantly as blood flow ceases and therefore convective transport is lost. In CCR, chest compressions are constant and thus maintain a steady blood flow, thus preventing extreme fluctuations in oxygen flux. Therefore, we conclude that CCR provides more oxygen to the blood and brain than CPR does.

Plan for Future Study

In future studies, we will examine the conditions under which air convection is present, oxygen concentration in the lung is non-constant, and blood flow is non-uniform throughout the capillary. In doing so we hope to observe the effects of blood flow and air flow to oxygen distribution within the capillary, and determine the effectiveness of CPR with breathing-tube and CPR without breathing tube in terms of their ability to deliver oxygen into blood stream.

We also plan to test our model on mesh independency and error analysis to check if our model is within the permit of error analysis.

References

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8. Berg RA, Kern KB, Hilwig RW, Ewy GA. “Assisted ventilation during ‘bystander’ CPR in a swine acute myocardial infarction does not improve outcome”. Circulation. 1997; 96: 4364 - 71

Appendix

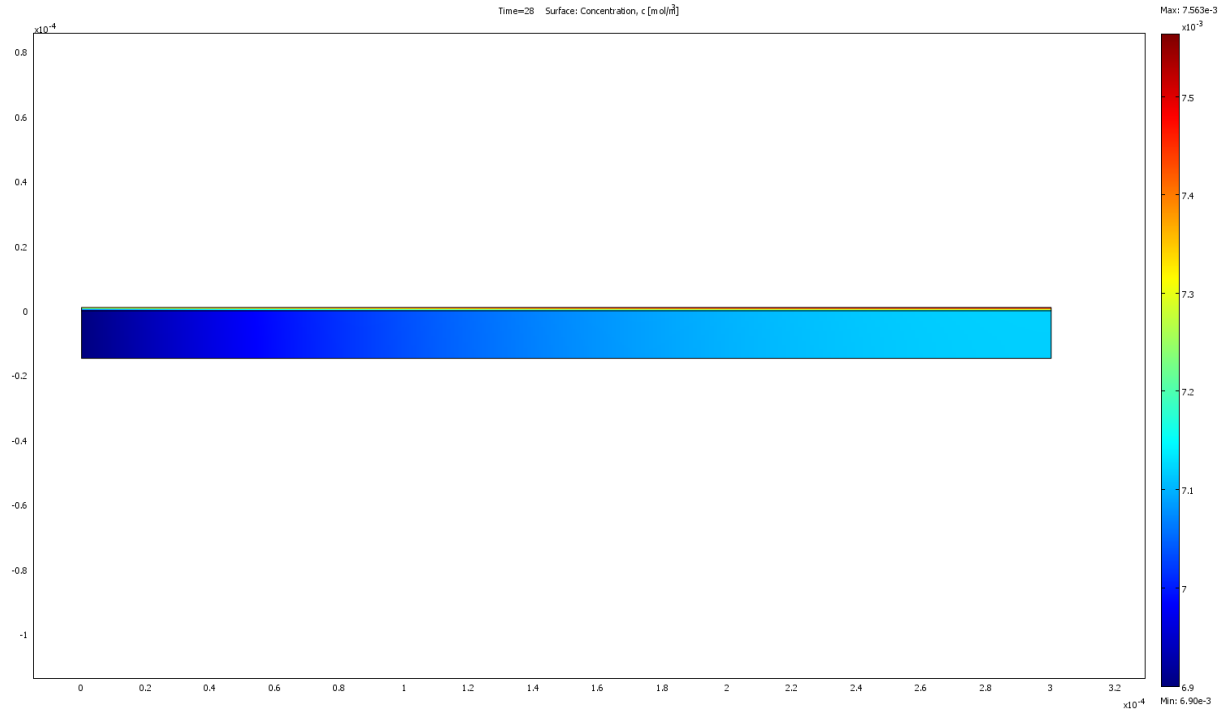

Figure 10. The concentration profile of the COMSOL model of a cycle of CPR (with rescue breathes).

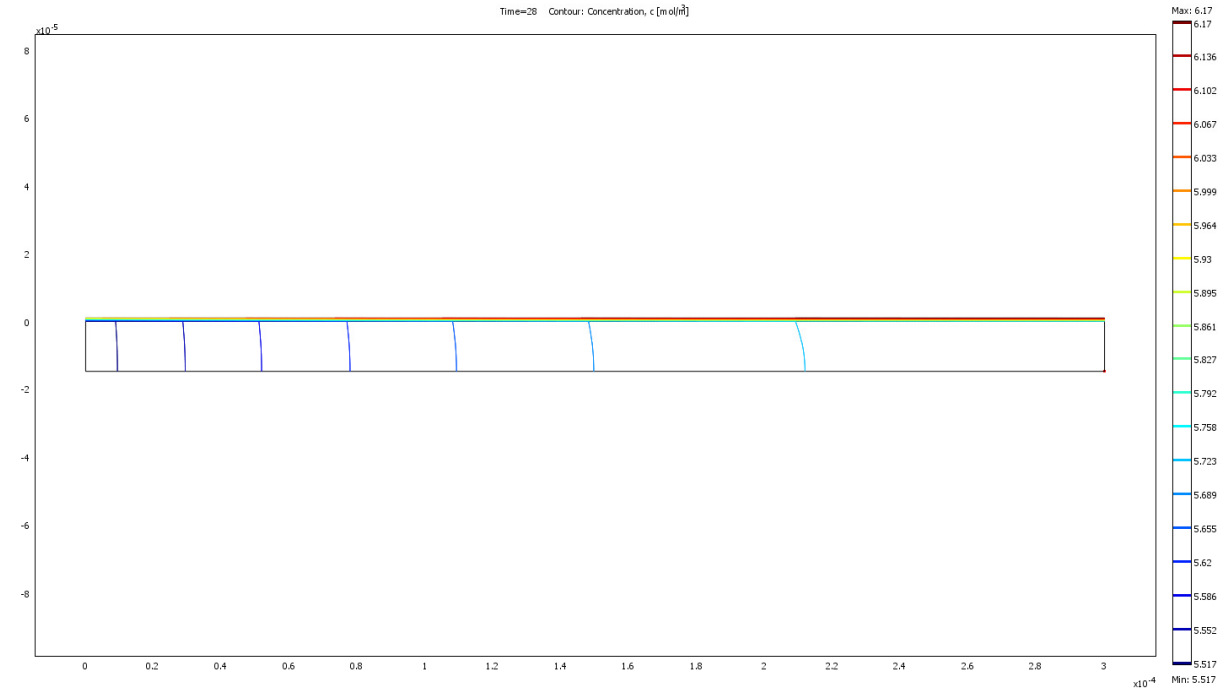

Figure 11. The contour plot of the COMSOL model of a cycle of CPR (with rescue breathes).

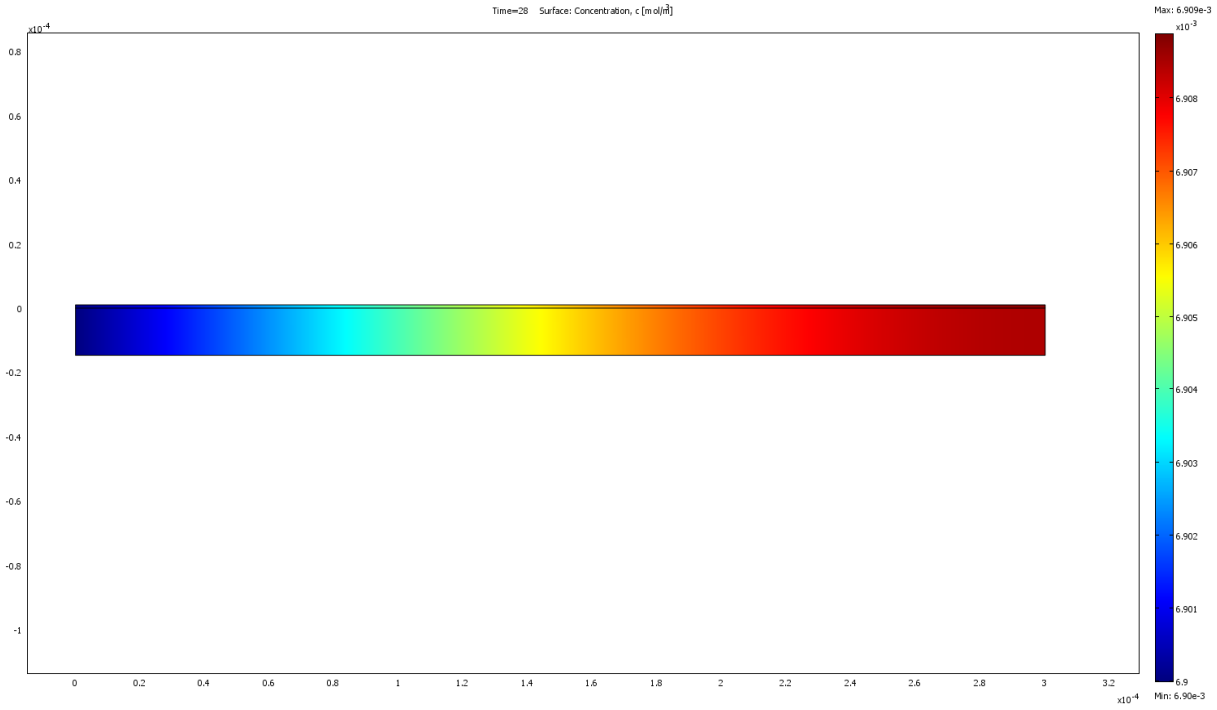

Figure 12. The concentration profile of the COMSOL model of a cycle of CCR (no rescue breathes).

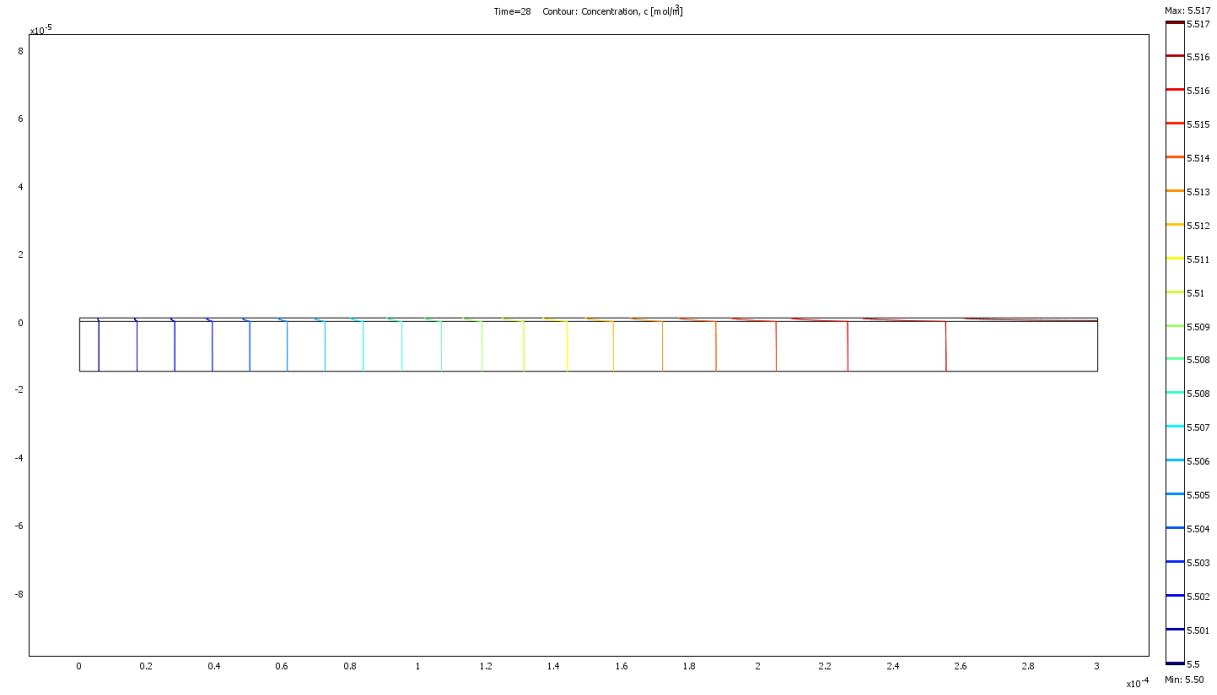

Figure 13. The contour plot of the COMSOL model of a cycle of CCR (no rescue breathes).

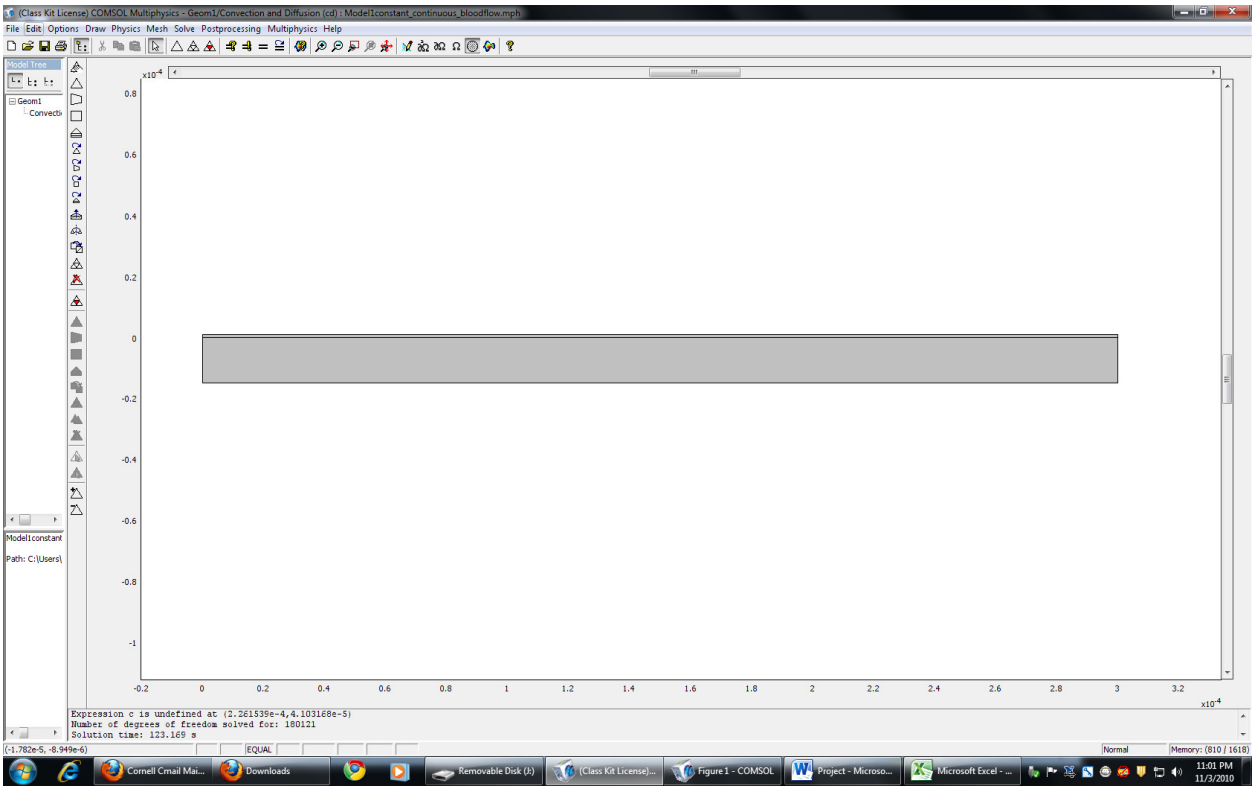

Figure 14. The final mesh for the COMSOL model at mesh convergence.

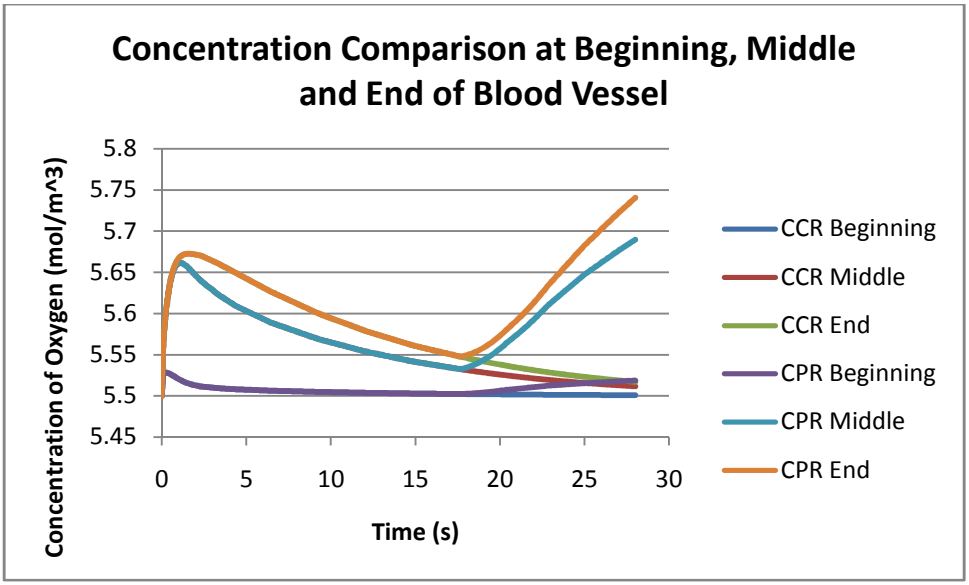

Figure 12. The comparison of the concentration of O_2 between CPR and CCR at the beginning, middle and end of the blood vessel that is being modeled.