SIMULATION STUDY OF BREAST TISSUE HEMODYNAMICS DURING PRESSURE PERTURBATION

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Abstract: We simulated the effects of compression of the breast on blood volume and tissue oxygenation. We sought to answer the question: how does the compression during breast examination impact on the circulatory systems of the breast tissue, namely blood flow, blood pooling, and oxygen concentration? We assumed that the blood was distributed in two compartments, arterial and venous. All the parameters were expressed with oxy- and deoxyhemoglobin quantities and were measured with a non-invasive method, Near Infrared Spectroscopy (NIRS). The simulated data showed that the blood volume pool in the breast decreased due to lower arterial flow and higher venous outflow, as the breast was squeezed under 100 cm H₂O with a 10 cm diameter probe (or 78 cm²). The blood volume was reversed when the pressure was released. The breast venous oxygen saturation dropped, but overall tissue saturation (presenting NIRS signal, volume weighted average saturation) was increased. The results showed that simulation can be used to obtain venous and average oxygen saturation as well as blood flow in compressed breast tissues.

1. INTRODUCTION

While breast examination for cancer prevention has been a routine practice, and external compression is always associated with it, effects of compression on the breast have not been fully investigated. The effects of compression of the breast have been studied regarding the mechanoreceptivity,¹ anatomical point of view,² relation to milk ejection,³ as the diagnostic tool,⁴ and in the optical property.⁵ The effect of compression on blood volume and oxygenation is of importance since it is the signature of cancer.⁶ While we did not find many previous studies on breast tissue, one study observed that
blood volume in a leg was reduced, and the study simulated an increase in the venous flow due to substantial pressure.\textsuperscript{7}

For this article, we simulated the relationships between compression and blood flow, and between blood reduction and oxygenation. With the simulation, we were able to calculate blood flow (arterial and venous) through the compression. This leads to a potential use of the simulation. The following equations allowed us to calculate blood flow, blood pooling, and oxygen concentration using hemoglobin kinetics data. These data sets can be obtained by a non-invasive procedure, Near Infrared Spectroscopy and Imaging, during a breast examination.

2. SIMULATION OF HEMOGLOBIN KINETICS

2.1. Simulation Equations

We established relationships between blood flow and tissue blood volume (BV) and oxygenation information using oxy- and deoxyhemoglobin quantities described as [HBO\textsubscript{2}] and [HB], respectively. What we gained from the NIRS signal were [HBO\textsubscript{2}] and [HB] and their changes. Addition of the quantities yielded blood volume, while subtraction yielded oxygenation, respectively, as follows:

\[ [\text{HBO}_{2}] + [\text{HB}] = \text{Blood Volume or } t[\text{HB}] \]  
(1)

\[ [\text{HBO}_{2}] - [\text{HB}] = \text{Oxygenation} \]  
(2)

In particular, changes of oxygenation occurring during compression are expressed as \( d[\text{HBO}_{2}] - d[\text{HB}] \), which is used to determine whether the tissue was oxygenated or deoxygenated.

Using a two compartment model, these two blood hemoglobin forms exist either in artery or venous vasculature. The following is a modified Fick's equation describing the relationships of blood flow and tissue blood information:

\[
d[\text{HBO}_{2}] / dt = Q_a - Q_v (S_{vO_2}) - M
\]  
(3)

where \( Q_a \) and \( Q_v \) are input (arterial) and output (venous) blood flows, expressed as velocity of hemoglobin mass mg/100 g tissue/sec. \( S_{vO_2} \) is saturation of hemoglobin with \( O_2 \) in the venous blood:

\[
S_{vO_2} = \frac{[\text{HBO}_{2}]_v}{[\text{HBO}_{2}]_v + [\text{HB}]_v}
\]  
(4)

\( M \) is the metabolic rate of the breast tissue, or oxygen consumption expressed as hemoglobin oxygen carrying capacity mg/100g tissue/sec.

We assume that the arterial blood consists of 100% HBO\textsubscript{2}, or \( S_{aO_2} = 1 \). The following equation explains that oxygen is extracted from HBO\textsubscript{2} with the rate of \( M \), and HBO\textsubscript{2} is converted to HB at the same time: