Muscle Microvascular Blood Flow, Oxygenation, and pH Decrease in Simulated Acute Compartment Syndrome

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Introduction: The current gold standard for diagnosing acute compartment syndrome (ACS) is based on clinical signs and the invasive monitoring of intramuscular pressure (IMP). However, despite accuracy and reproducibility, several shortcomings are associated with IMP measurements, such as the risk of infection, pain, and a lack of agreement about the diagnostic pressure threshold [6]. Therefore, it is important to identify alternative non-invasive and accurate diagnostic tools. Previously, ultrasound, MRI, photoplethysmography (PPG), and near-infrared spectroscopy (NIRS) have been evaluated as diagnostics but not implemented clinically [2]. The objective of this study was to evaluate muscle hemodynamics, tissue oxygenation and pH as diagnostic parameters in a model ACS using PPG and NIRS. We hypothesized that as IMP increases, muscle microvascular blood flow, oxygenation and pH will decrease in a leg at heart level and significantly more when elevated.

Methods: An external pneumatic leg pressure chamber [2], combined with a venous stasis thigh cuff, were used to increase IMP and simulate ACS. Microvascular blood flow was measured noninvasively using PPG, which consists of a light emitting diode and a photodetector [3]. Muscle oxygenation (100% maximal and 0% minimal muscle oxygen saturation) and pH (device calibrated pH unit) were measured noninvasively using a NIRS-pH device (CareGuide™) [4]. Eight healthy subjects (5M, 3F, mean age of 26 years and mean blood pressure of 121/71 mm Hg) had sensors placed on the middle anterior tibialis of the right experimental leg and left control leg (no external pressure or thigh cuff). Leg chamber pressure conditions (40, 50 and 60 mmHg) were applied in a randomized order after baseline measurements were collected. A thigh blood pressure cuff was placed around the right thigh, approximately 4 inches above the knee. A tourniquet pressure of 65 mmHg was used to induce venous stasis during external pressure conditions. Data were collected continuously for each 11-minute pressure condition, and the last six minutes were used for data analyses. An 11-minute recovery period (chamber pressure = 0 mmHg and deflated thigh cuff) followed each pressure condition. The same protocol was repeated with each subject’s legs (control and experimental) elevated 12 cm above heart level. Blood pressure was measured for each subject on both ankles at baseline and on the right arm during the last two minutes of each pressure condition. Data were analyzed using repeated measures ANOVA, with main effects side (experimental and control leg) and pressure (baseline, 40, 50, 60 mmHg, recovery), and position (heart-level and elevated legs). A p<0.05 was used to determine statistical significance. All data are presented as means ± SEM.

Results: Muscle microvascular blood flow, oxygenation and pH did not significantly decrease in the control leg at all pressure conditions (supine and elevated). As IMP increased, blood flow (p=0.01), muscle oxygenation (p<0.001) and pH (p<0.001) all decreased significantly in the experimental leg compared to the control leg (Figure 1). Mean microvascular blood flow decreased from 1.48±0.13 to 1.26±0.23, 0.97±0.24 and 0.76±0.24 (volts) at external pressures of 40, 50 and 60 mmHg, respectively. Mean muscle oxygenation decreased in the experimental leg from 76.4±1.0 at baseline to 69.0±1.7, 65.3±3.4 and 59.7±4.5 (SmO2), at external pressures of 40, 50 and 60 mmHg, respectively. Mean muscle pH decreased from 7.48±0.00 to 7.38±0.04, 7.37±0.04 and 7.31±0.04 at external pressures of 40, 50 and 60 mmHg, respectively. At all IMP levels, leg elevation significantly decreased (p=0.003) muscle oxygenation compared to the leg at heart level. Compared to the leg at heart level, elevated leg mean muscle oxygenation decreased from 73.0±1.9 at baseline to 66.6±1.5, 55.7±4.4 and 44.8±4.5 (%) at IMPs of 40, 50 and 60 mmHg, respectively. However, muscle pH and blood flow did not decrease significantly more in the leg elevated than the leg at heart level.

Discussion: Our results indicate that muscle blood flow, oxygenation and pH decrease significantly as IMP increases in a model acute compartment syndrome. It has been proposed that perfusion pressure (AP) calculated as, Mean Arterial Pressure - Intramuscular Pressure, is more valuable in diagnosing ACS. Leg elevation decreases AP and tissue tolerance to ischemia during elevated IMP [5]. Our data support this proposition, as tissue oxygenation is further significantly decreased with leg elevation. Previous research by our group demonstrates that IMP correlates linearly with chamber pressure without a thigh cuff [2]. Future studies will compare these noninvasive measures to invasively measured IMP with external pressure and thigh cuff application.

Significance: Our study identifies metabolic and hemodynamic parameters as potential diagnostic tools for ACS. This oximeter device [1] is non-invasive, enables direct comparisons to an intact contralateral muscle, and therefore may provide a new ACS diagnostic tool.

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Figure 1. Muscle blood flow (p<0.01) and oxygenation (p<0.001) significantly decreased as intramuscular pressure increased in both the heart-level and elevated legs, as compared to baseline. Leg elevation resulted in further decrease in muscle oxygenation (p<0.003) at all pressure conditions but not in blood flow and pH. Muscle pH (p<0.001) decreased as intramuscular pressure increased in both the heart-level and elevated legs. The solid horizontal line represents the average tissue oxygenation of the heart-level control leg and the dashed line represents the average tissue oxygenation of the elevated control leg.