Correlation of Altitude and Compartment Pressures in Porcine Hind Limbs

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Recent wartime contingencies have demanded frequent aeromedical evacuation of polytrauma patients, all with risk factors for the development of compartment syndrome. This study investigated the effect of altitude on the pressure in uninjured myofascial compartments of 10 pigs as part of a program with the ultimate goal of determining the behavior of an injured extremity in a changing altitude environment. The data showed a trend toward a small increase in pressure with increase in altitude — an average maximal delta of 2.7 mm Hg from the opening pressure. A small increase in compartment pressure, such as seen in this study, in a normal, uninjured compartment would likely go clinically unnoticed. However, aeromedical evacuation missions fly patients with fractures that can affect the physiology of compartments. Potentially, even a small change in pressure can lead to a compartment syndrome. Further study involving a fracture model will be required to further elucidate this clinical question. (Journal of Surgical Orthopaedic Advances 20(1):30–33, 2011)

Key words: compartment syndrome, critical care aeromedical transport (CCAT)

The evacuation of critically injured patients from forward locations has played a vital role in the medical care delivered to coalition forces in the current wars in Iraq and Afghanistan. Critical care aeromedical transport (CCAT) teams can quickly move patients with devastating injuries from forward field hospitals to interim care locations in Germany to definitive level care in the United States. The aircraft tasked with the CCAT missions have the capability to provide a pressurized cabin with an adjusted altitude of about 10,000 feet above sea level. As such, the patient will experience a relative altitude climb of 10,000 feet, affecting various aspects of normal and pathophysiology. One area of particular interest is extremity compartment pressure during these flights. Due to the decreased ambient pressure (increase in altitude), nitrogen accumulates in the muscles. Nitrogen acts as an osmotic agent, leading to edema and thus muscle swelling. However, the amount of increase and clinical significance is thus far unknown. It stands to reason that patients with injuries that cause noncritical increases in intracompartmental pressures at ground level can ultimately have further increasing pressures at altitude and possible neurovascular compromise.

Compartment syndrome is a devastating complication in orthopaedic trauma, leading to a possible limb- or life-threatening situation for the patient. Recent wartime contingencies have demanded frequent aeromedical evacuation of polytrauma patients. Many of these patients have significant long-bone injury along with massive soft tissue trauma — all risk factors for the development of compartment syndrome. Anatomic compartments normally maintain a relatively stable pressure within their fascial boundaries. However, the effect of rapidly increased altitude, such as seen in aeromedical flight profiles, has not been studied in a large animal model. Induction of compartment syndrome, however, has been demonstrated successfully in the uninjured limbs of both porcine and canine models (1–3). This study investigates the effect of altitude on the pressure in normal, uninjured myofascial compartments of porcine hind limbs. The hypothesis is that the altitude changes seen in a standard aeromedical flight profile do not affect normal compartment pressures.

Materials and Methods

Eleven male pigs (*Sus scrofa*) were used for this study. Intravenous access was achieved by the veterinary team with catheterization of the internal jugular vein. Each pig was anesthetized before having the compartment pressure-monitoring devices placed into the anterior compartment of its right hind limb. Anesthesia was accomplished using a medication regimen consisting of ketamine

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(15–20 mg/kg), acepromazine (0.11–0.22 mg/kg IM), and atropine (0.04–0.4 mg/kg). After prepping the area with betadine, a small incision was made over the anterior compartment and the fascia was exposed. This ensured the correct placement of the catheter. An 18-gauge side port catheter needle was introduced through the fascia and into the peroneus tertius muscle and then secured into place using silk tape. The pig was then moved into the laboratory altitude chamber, which was used to achieve the desired flight profile. The tubing was run out of the altitude chamber through an airtight seal augmented with silicon, and a digital pressure monitor (Stryker Medical, MI) was connected in line with the catheter and tubing. Five feet of tubing was used in total: 3 feet inside the chamber and 2 feet outside the chamber. Figure 1 illustrates the test chamber setup. The pressure monitor was normalized (zeroed) at the level of the pig. The pigs were flown to an altitude of 10,000 feet consistent with the flight profile of an aeromedical evacuation flight. The flight consisted of a constant climb rate of 2500 feet per minute to an altitude of 10,000 feet, then level flight for 5 hours, followed by a controlled descent of 2500 feet per minute until reaching ground level. Constant monitoring of the pig's anterior compartment was conducted over a 6-hour period with measurements being taken every 30 minutes. After the flight profile was completed, the pigs were removed from the altitude chamber, a final pressure was recorded, and the pressure-monitoring device was discontinued.

The data were normalized in a graphical representation where the opening pressure was considered zero, and each subsequent data point was represented as the difference, either positive or negative, from that point and the opening pressure.

Results

A total of 11 pigs were flown in the altitude chamber. One pig expired secondary to anesthesia before any measurements were taken and was not included in the study group. Data from a second pig were further excluded secondary to technical error with the monitoring equipment. This left data points from nine subjects for analysis. One subject's altitude chamber run was cut short (4 hours) secondary to the pig emerging from anesthesia, but the data were included in the analysis because the run represented a minimum aeromedical evacuation flight time.

Table 1 shows the delta values of the pressure measurement in the nine pigs. The delta values were then plotted on a scatter graph. The average delta value at each time point was then plotted on the same graph (Fig. 2). The maximum deviation in pressure from the opening pressure was 6 mm Hg. The average maximum deviation in pressure from opening pressure was 2.7 mm Hg.

Discussion

In the current conflict in the Middle East, the United States and coalition injured servicemen and women are rapidly being evacuated to points outside of the war zone. During the evacuation process, the injured must withstand a long aircraft flight, often for more than 4 to 6 hours. Anecdotally, there have been numerous incidents of compartment syndrome following these flights. However, it is unclear if these incidents of compartment syndrome were in existence before the flight and had gone unnoticed, exacerbated on the flights, or caused by the flights.

This study represents a pilot program with the ultimate goal of determining the behavior of an injured

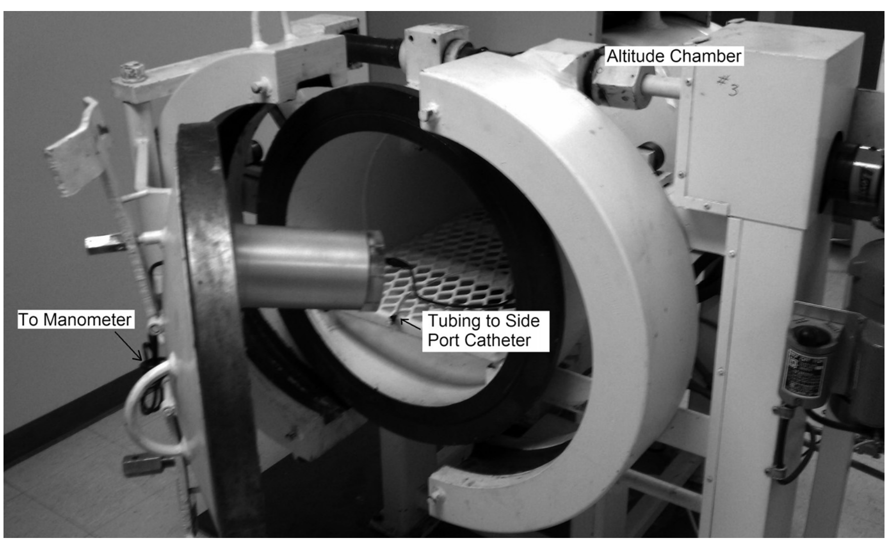

FIGURE 1 Test chamber setup.

TABLE 1 Compartment pressure change during flight time

Hour	Pig 1	Pig 2	Pig 3	Pig 4	Pig 5	Pig 6	Pig 7	Pig 8	Pig 9	Average
0	0	0	0	0	0	0	0	0	0	0
0.5	2	2	6	0	2	1	1	2	−1	1.6
1	1	3	−1	−1	5	1	−1	2	−1	0.8
1.5	2	3	2	0	4	1	1	2	1	1.7
2	0	1	−2	2	4	3	2	5	2	1.8
2.5	0	2	0	2	4	4	5	4	4	2.7
3	−1	2	0	1	4	4	5	4	4	2.5
3.5	0	1	0	0	4	3	4	5	4	2.3
4	0	0	0	−3	4	1	4	3	5	1.5
4.5	0	−1	0		4	2	5	3	2	1.8
5	4	0	0		5	1	4	2	0	2
5.5	0		2		3	0	2	1	0	1.1
6	0		0		2	0	1	1	0	0.5
6.5	0		1		1	1	1			0.8

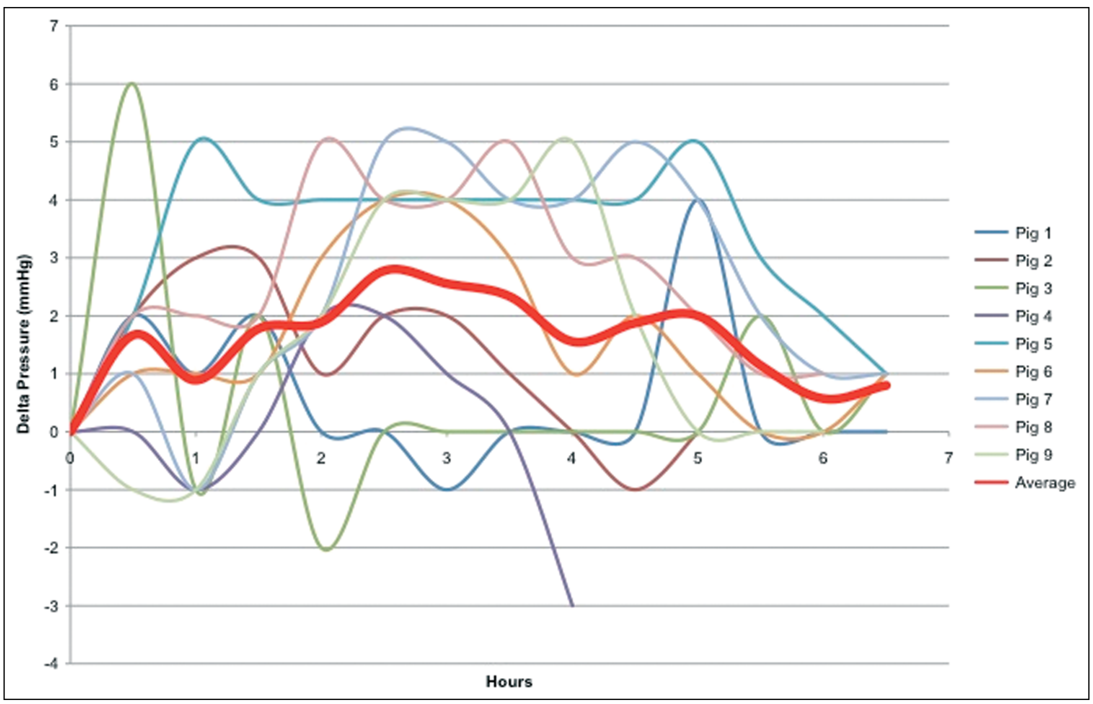

FIGURE 2 Graph displaying the change in compartment pressures during altitude chamber flight time.

extremity in a rapidly changing altitude environment, as seen in aeromedical evacuation missions. This study aims to elucidate the possible effects of altitude on anatomic compartments. Answering this question could lead to the implementation of critical practice guidelines improving overall health and management of military members who are injured in combat.

The initial step in determining the behavior of injured compartments' response to increase in altitude is to model the behavior of the normal compartment. Previous studies of compartment syndrome have been accomplished using a pig model. The pigs' physiology and response to compartment syndrome mimic what is encountered in humans (4).

The hypothesis that a flight profile such as seen in a CCAT flight has no effect on the overall compartment pressure of a normal, uninjured compartment was disproved. However, our data showed that the change in pressures in an uninjured compartment in response to altitude is not dramatic. There was a trend toward a small increase in pressure with increase in altitude. This trend was minimal — an average maximal delta of 2.7 mm Hg from the opening pressure. In addition, the increase in pressure eventually returns to near opening pressure as the altitude returns to ground level during the end of the flight.

A significant question posed from the results is whether a 2- to 3-mm Hg change in compartment pressure is clinically significant. The definition of compartment syndrome is not an absolute. Compartment pressures can be considered significant as an absolute number or as a difference from the diastolic blood pressure or mean arterial pressure. Mubarak et al., in 1978, noted that an absolute compartment pressure of 30 mm Hg or greater for more than 6 hours caused irreversible muscle necrosis (5). In a study of 17 patients, Ouellette and Kelly, in 1996, showed that compartment syndrome was seen with a compartment pressure of 15 mm Hg with signs of pain or parasthesias (6). Allen et al., in 1985, asserted that no adverse sequelae were seen with a cutoff pressure of 40 mm Hg (7). Alternatively, Whitesides et al. and McQueen consider compartment syndrome if the diastolic blood pressure minus the compartment pressure is less than 30 mm Hg (8, 9), while Mars and Hadley note that the mean arterial pressure is a more accurate measure (10).

A small increase in compartment pressure, such as seen in this study, in a normal, uninjured compartment would likely go clinically unnoticed. However, CCAT missions transport injured United States and coalition forces with fractures that can affect the physiology of compartments. Potentially, even a small change in pressure can lead to a compartment syndrome. Further study involving a fracture model will be required to further elucidate this clinical question.

Several limiting factors were identified in this study. The first involved delivery and titration of anesthesia to the subjects. Although competently trained veterinary staff members were employed, there was difficulty in obtaining and maintaining vascular access during flight for several pigs. Variability in dosing of medications presented a challenge with sedating the animals for the duration of their flight profiles. Occasionally, the animals would awaken before the completion of their 8 hours in the altitude chamber, which may have led to altered pressure measurements due to muscle contraction. One animal was unintentionally euthanized due to overdosage of medication in preflight before any measurements were taken.

In addition, the decision to perform a fasciotomy may be based on compartment pressure measurements in the setting of an equivocal clinical exam. Blood pressure measurements were not recorded in this study. The use of an arterial line for recording blood pressure may have been a more appropriate and applicable way to monitor compartment pressures in this study. In addition, normal variability of pressure in the tubing through the altitude range was not considered. However, the setup was consistent throughout the entire study with each subject and therefore each pig was subjected to similar normal pressure variability.

Summary

Based on the results of this study, our hypothesis that a flight profile such as seen in a CCAT flight has no effect on the overall compartment pressure was disproved. The change, however, was very small — an average of 2.7-mm Hg maximum deviation from opening pressure. The clinical relevance of this change still needs to be elucidated with further study. In addition, evaluation of altitude changes on an injured compartment (fracture, soft tissue damage) is still forthcoming.

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