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Efficacy of Cardiopulmonary Resuscitation in the Microgravity Environment

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Background: End tidal carbon dioxide ($EtCO_2$) has been previously shown to be an effective non-invasive tool for estimating cardiac output during cardiopulmonary resuscitation (CPR). Animal models have shown that this diagnostic adjunct can be used as a predictor of survival when $EtCO_2$ values are maintained above 25% of prearrest values.

Hypothesis: CPR can be administered in the microgravity environment.

Methods: Eleven anesthetized Yorkshire swine were flown under the simulated microgravity conditions on a KC-135. Physiologic parameters including $EtCO_2$ were monitored. Standard Advance Cardiac Life Support protocols were used to resuscitate these models after induction of cardiac arrest. Chest compressions were administered using conventional body positioning with restraint and unconventional vertical-inverted body positioning.

Results: $EtCO_2$ values were maintained above 25% of prearrest values in the microgravity environment (33%± 3 ground and 41%± 3 flight controls). No significant difference in CPR, as monitored by $EtCO_2$, administered in 1G or 0G on these models was noted (Ground Control : 35± 3% 1-g vs 33± 3% 0-g; Flight Control: 44± 3% 1-g vs 41± 3% 0-g). Effective CPR was delivered in both body positions although conventional body positioning was found to be fatiguing.

Conclusions: Cardiopulmonary pulmonary resuscitation can be effectively administered in microgravity. Validation of this model has demonstrated that $EtCO_2$ levels were maintained above a level previously reported to be predictive of survival. The unconventional vertical-inverted position provided effective CPR and was less fatiguing as compared to the conventional body positioning.

Key Words: Cardiopulmonary Resuscitation, End-tidal CO_2, Space Medicine, Advanced Cardiac Life Support, Weightlessness

Introduction

The inherent risks of space flight are significant. Recently, Johnston *et al* characterized the medical risks associated with long duration space flight (1). In this analysis, data was abstracted from the Russian Space Program, the Longitudinal Study of Astronaut Health (LSAH), and analog populations such as winter-over groups in Antarctica and military submarine crews. These data showed that for a crew of seven astronauts the incidence of a significant medical event was once every 2.4 years and the incidence of an incapacitating medical emergency was once every 14 years.

Although routinely used, cardiopulmonary resuscitation (CPR) and Advanced Cardiac Life Support (ACLS) (2) are relatively new techniques when viewed from the perspective of the history of medicine (3). Even under optimum circumstances, cardiac and cerebral perfusion pressures are but a fraction of pre-arrest values (4, 5). For this reason, survivability decreases precipitously when the initiation of CPR is delayed. The primary motive force behind the generation of perfusion pressures is related to the increase in intra-thoracic pressures during CPR as opposed to direct cardiac compression (6).

Animal models and human studies have shown that end-tidal CO_2 ($EtCO_2$) monitoring is an accurate adjunct with which to monitor the efficacy of CPR (7-14). These studies showed that during the low blood-flow states associated with CPR, $EtCO_2$ monitoring is a reliable detector of pulmonary blood flow and therefore cardiac output (CO). Although preliminary studies suggested this relationship to be linear (14), more recent investigations have shown a near-linear relationship (11). This relationship to CO is important because coronary perfusion, which is a predictor of the return of spontaneous circulation (ROSC), is directly related to CO (15, 16). It is through this link to CO that $EtCO_2$ has been shown to correlate with cerebral perfusion pressure as well (10).

Recently, human trials have attempted to define an $EtCO_2$ level that is predictive of survivability after the initiation of CPR (8, 12, 13, 17, 18). In their porcine model, Gudipati *et al* showed that the ability to maintain $EtCO_2$ values at greater than 25% of prearrest values was an accurate predictor of survivability (9). The objective therefore of this study was to demonstrate that CPR could be effectively administered in a microgravity environment. $EtCO_2$ monitoring in addition to monitoring of blood pressure and oximeter levels were used to monitor the effectiveness of CPR in this microgravity model.

CPR is difficult to deliver in the weightless environment, as chest compressions have to be counter acted by the CPR provider. This usually done by gravity in the normal 1-g environment, but in the 0-g weightless environment must be performed by either restraint, bracing, or active muscular counteraction by the CPR provider. Depending on how much active muscular reaction is required, this can be extremely fatiguing.

In addition, in the 0-g environment, CPR can only be performed if there is a method of restraint of the patient, CPR provider, and all equipment. A floor level restraint system was developed for medical restraint in weightlessness and this project was a demonstration of its effectiveness. This Crew Medical Restraint System (CMRS) provided restraint of the animal model, all ACLS equipment and hardware, and methods for CPR provider restraint.

Materials and Methods

Experimentation was conducted as part of a program to assess ACLS and Advanced Trauma Life Support (ATLS) protocols in the microgravity environment. As part of this program, a total of eleven pigs were flown in a modified KC-135, which is able to simulate microgravity. By using parabolic flight, a KC-135 is able to provide forty-second intervals of zero gravity (0-g) followed by a 2-g pullout. A total of eleven flights, one for each porcine model, were conducted with 40 parabolas on each flight. These models were run in groups of three and experimentation was conducted in 1992, 1993, 1996, and 1998.

Yorkshire swine were chosen as the porcine test model. The models had not undergone previous testing. The initial three models were 20-23 kg while the remaining eight weighed 50 kg. Strict adherence to the Standard Anesthetic Regimen, Surgical Training Lab Protocols, and Guide to Care and Use of Laboratory Animals, NIH Publication #86-23 was maintained. In accordance with KC-135 flight rules that prohibit the use of inhalational anesthetics, intravenous pentobarbital was used as the general anesthetic. This study received review, approval, and monitoring by the St. Joseph Hospital Surgical Training Lab Institutional Animal Care and Use Committee (Houston, Texas), by the NASA-JSC Institutional Animal Care and Use Committee (Houston, Texas), and the NASA-JSC Institutional Review Board (Houston, Texas).

Animals were initially prepared at the Surgical Training Lab at St. Joseph's Hospital. After receiving an intramuscular dose of Ketamine (5cc/kg), the swine were orotracheally intubated and initiated on halothane gas general anesthesia. The animal was ventilated with 12-15 breaths per minute with a tidal volume of 10 ml/kg. Each specimen was prepped and draped in a sterile fashion and the central vasculature of the neck mobilized surgically. An arterial line in the carotid artery was placed for blood pressure monitoring followed by the placement of a central line in the jugular vein for the administration of fluids and medications. Peripheral venous access was also obtained via percutaneous introduction of an angiocatheter into an ear vein. The method of general anesthesia was then changed to intravenous with pentobarbital (0.25cc/kg) and paralysis was maintained with Pancuronium (0.09 mg/kg/hour). Maintenance of adequate anesthesia was titrated based on continuous monitoring of vital signs. The porcine models were then transported Ellington Field (Houston, Texas) with a total time for prepping to arrival of 90 minutes. At the completion of all testing, the animals were euthanized using IV Pentothal and disposed of by the Surgical Training Lab at St. Joseph's Hospital.

Each animal was monitored continuously throughout experimentation. A physiologic monitoring module (Spacelabs Medical Inc, Redmond, WA) was used to monitor intra-arterial blood pressure, cardiac rhythm strip, rectal temperature, oximetry (via a tongue-probe), and end-tidal CO2 (Novametrix Medical Systems, Inc., Wallingford, CT). A pneumatically powered ventilator (LAMA), which had been previously rated for microgravity flight was used throughout the study. Due to safety restrictions, compressed air instead of 100% oxygen was used when aboard the KC-135. This provided a SaO2 of 94 ± 1% on the ground and 88 ± 2 % at a flight cabin pressure of 6000-8000 feet. Ventricular fibrillation was induced with an intravenous bolus of potassium chloride (KCl). After verifying induction of ventricular fibrillation through cardiac monitoring and drop in arterial blood pressure, chest compressions were performed by several CPR providers. A commercially available defibrillator/pacer unit (Physio-Control Lifepak-10, Redmond, WA), weight-adjusted ACLS medications, and standard ACLS algorithms were then used to regain spontaneous rhythm.

Two methods were used by CPR providers to perform manual chest compressions. The first method was a conventional body position with the CPR provider to the side of the animal model and restrained by waist belts and/or restraint cords across the lower legs (**Figure 1**). This method required a

large amount of effort by the CPR provider to counter act the force of the chest compressions and was known to be quickly fatiguing from earlier parabolic flights utilizing manikins. The second method was with the CPR provider in the unconventional vertical-inverted position with his feet on the ceiling which allowed for bracing to counter act the force of the chest compressions (**Figure 2**). Obviously, this position can only be used during weightlessness. This position was also known from previous parabolic manikin studies to allow for the performance of CPR with only minimal effort.

Physiologic parameters were measured under the following conditions: 1) ground controls were obtained preflight at 1-g during normal sinus rhythm (NSR) 2) flight controls obtained in flight at 1-g and with NSR 3) at altitude during 1-g CPR 4) at altitude during 0-g CPR. Five data points were obtained under each of these conditions and averaged. The $EtCO_2$ data is expressed as % of $EtCO_2$. Data is presented graphically with 95% confidence intervals included. T-tests are used where P-values are computed.

Results

Figure 3 contains a sample graph of the physiologic parameters monitored during each KC-135 flight. Note that the onset of ventricular fibrillation, which was induced by intravenous potassium chloride, was immediately reflected in the vital signs. During each flight, the porcine model was oriented in parallel with the long axis of the airplane.

Mean oximeter readings are reported in **Figure 4**. As was documented previously, due to flight rules supplemental oxygen was not available during the KC-135 flight. This was reflected in the oximeter readings that are taken at an effective altitude of 6-8000 feet above sea level. This resulted in a significant change in the SaO_2 readings with a mean ground control reading of 94 ± 1% and a mean flight control reading of 89 ± 2% (P= 0.0001). No statistically significant differences were noted between the oximeter readings taken during CPR in the micro- or normogravity. The oximeter readings for both CPR groups were significantly lower than both controls.

Figure 5 presents the $EtCO_2$ results in terms of percentage of control. Both the percentage of ground and flight controls are presented for analysis. These data show that CPR in the microgravity environment was able to sustain $EtCO_2$ values well above 25% of prearrest values when compared to both the ground and flight controls. No significant differences in mean $EtCO_2$ readings were noted between

CPR performed under 1-g or 0-g when comparing the ground (35 ± 3% 1-g vs 33 ± 3% 0-g) and flight (44 ± 3% 1-g vs 41± 3% 0-g) control results separately. There was a trend towards statistical significance noted between $EtCO_2$ readings of the ground versus flight CPR results. Although statistically significant, the difference between these two values would be of questionable clinical significance as Gudipati was not able to demonstrate any relationship between survivability and $EtCO_2$ readings beyond an increased likelihood of survival above the 25% of prearrest value (9).

The mean intra-arterial blood pressure results are presented in **Figure 6**. As expected, the onset of ventricular fibrillation produced a significant change in pressure. No other significant trends in the mean blood pressure were noted during CPR conducted in either the micro or normogravity settings.

There was no difference in any of the monitored parameters (SaO2, EtCO2, and intra-arterial BP) between the two methods of chest compression.

Discussion

This study has several limitations. First, while the KC-135 provides the most representative microgravity experience without actually being in orbit, the duration of 0-g exposure during each parabola is only 30 seconds. As noted previously, one KC-135 flight typically consists of forty such parabolas. Interposed between each 0-g parabola of periods of up to 2-g. To maximize the effect of microgravity on this model, all readings taken under microgravity conditions were recorded 25 seconds into each parabola to maximize the effect of 0-g. Classically, physiology texts teach that carbon dioxide diffusion across the lung parenchyma is essentially instantaneous (19). It is not clear how the low flow states associated with CPR impact this relationship. Some studies have suggested that the diffusing capacity of CO_2 is delayed. It is not clear to what extent this impacts our investigation.

As noted previously, oxygen supplementation was not provided during in-flight experimentation due to airplane safety restrictions. Administration of high-flow oxygen is one of the basics of resuscitation and is standard of care in terrestrial medical operations. Additionally, our investigations were performed under the hypobaric environment (10.7-11.7 psi) provided in the KC-135. Despite the absence of optimum oxygenation, the ability to maintain $EtCO_2$ levels above a prescribed level was demonstrated.

The International Space Station is designed with 14.7 psi or 1 atmosphere of pressure and supplemental oxygen will be available.

A final limitation is that these porcine models were also used to test ATLS techniques. All of these procedures, including chest tubes and peritoneal lavage, were completed prior to ACLS Mega-code testing. This sequence is routinely performed in medical residency animal training procedures. It is not clear what if any affect these other investigations had on experimental results. However, with consideration to the presented results, it would suggest that our results weren't adversely biased. Furthermore, although these models were not deconditioned as would an analogous astronaut be, it does suggest that this can be successfully performed on an individual with significant trauma.

This study demonstrated several important findings. First, as demonstrated by decrements in oximeter results during CPR, supplemental oxygen would be an important adjunct for any scenario requiring these procedures. Furthermore, should subsequent transport be required, several studies have documented further decrements in oximeter readings and arterial PaO2 values in healthy individual exposed to the hyper-gravity conditions associated with orbital reentry(20, 21). These parameters would be further compromised in a medically incapacitated patient and oxygen supplementation would assist in optimizing outcome.

Second and most importantly, with respect to the predictive capabilities of $EtCO_2$ and survivability, Gudipati reported that $EtCO_2$ values less than 25% of prearrest were predictive of mortality(9). Tervino, in a similar porcine study, showed comparable results (22). This study demonstrates no significant differences between $EtCO_2$ values obtained during CPR under 1-g and 0-g conditions. More importantly, in both of these experimental CPR conditions, the $EtCO_2$ percent of control was maintained well above the 25% described previously. This was demonstrated both in our ground and flight control conditions. Due to the relationships between $EtCO_2$, CO, and cardiac perfusion pressures as well as link between the percentage $EtCO_2$ and survivability, we believe that this supports the hypothesis that effective CPR can be delivered in the microgravity environment.

Both methods of chest compressions, the conventional body position with restraints and unconventional vertical-inverted, were found to provide adequate and equivalent CPR. However, the conventional method was quickly fatiguing and the unconventional vertical-inverted method required

minimal effort by the CPR providers. As the dimensions of the KC-135 cabin are similar to the interior dimensions of the ISS modules, the vertical inverted method is a suitable technique for the administration of chest compressions during CPR in space flight. Current designs, however, will utilize the conventional restrained configuration in conjunction with the crew medical restraint system so as to place the health-care provider in close proximity to the patient for concerns regarding maintenance of airway, drug administration and other therapeutic considerations.

Although beyond the scope of this discussion, this investigation has resulted in the adaptation of ACLS Mega-code procedures and validation of space-rated hardware for inclusion in the International Space Station's Health Maintenance System (HMS). During the course of this investigation a defibrillator, intravenous fluids and medications, and a ventilator were reliably used and manifested for space flight. A floor level Crew Medical Restraint System (CMRS) was demonstrated to be able to provide adequate restraint for the performance of ACLS by providing for patient, hardware, and CPR provider restraint. The inclusion of these devices in the HMS will extend the medical capabilities to provide care for the critically ill and/or injured.

Finally, validation of this microgravity CPR model has allowed for its' use as a training model. Currently, the crew medical officer (CMO) is trained to have at least emergency medical technician capabilities and may in some cases be a physician depending on the individual. Two individuals have received training on this model prior to their shuttle flights. Additionally, investigations into the utility of $EtCO_2$ during CPR have also shown that it can be effectively used to monitor fatigue and effectiveness of compression being administered (23-25). Preflight training on this model would allow a CMO to become familiar with the actual mechanics of performing cardiac compressions in microgravity as well as providing exposure to and familiarization with on-orbit hardware. This in combination with proposed on-orbit computer training modules (26), could provide a means for future long-duration crews to obtain and maintain medical proficiencies.

In conclusion, this investigation into CPR in microgravity has demonstrated 1) the ability of maintain $EtCO_2$ values above previously reported values predictive of survivability in both the 1G and 0G models 2) no change in mean intra-arterial pressures generated by external cardiac compression during

CPR in microgravity 3) decrements in oxygen saturation related to our experimental conditions and 4) demonstrated effective administration of CPR in both the conventional and vertical-inverted positions.

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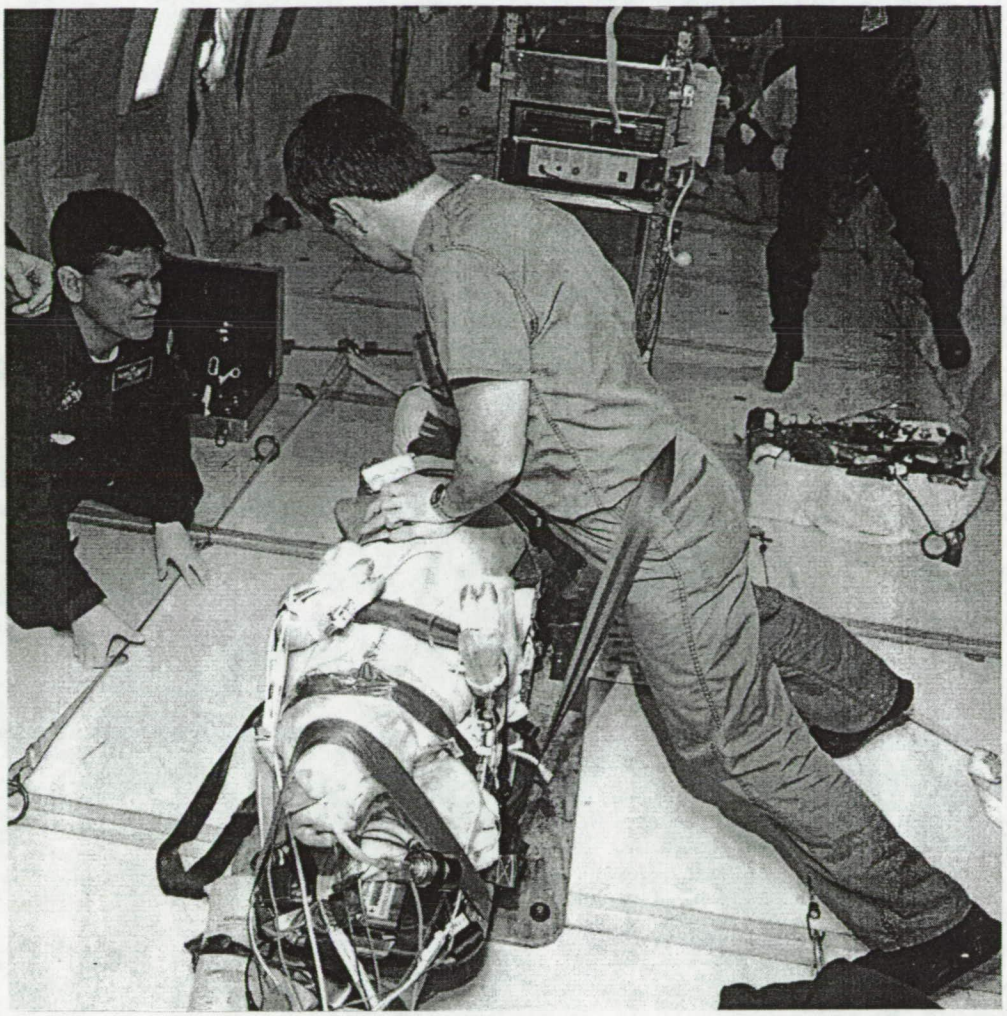

Figure 1: Conventional Restrained CPR

Figure 2: Vertical-Inverted CPR

Figure 3: ACLS Code Summary

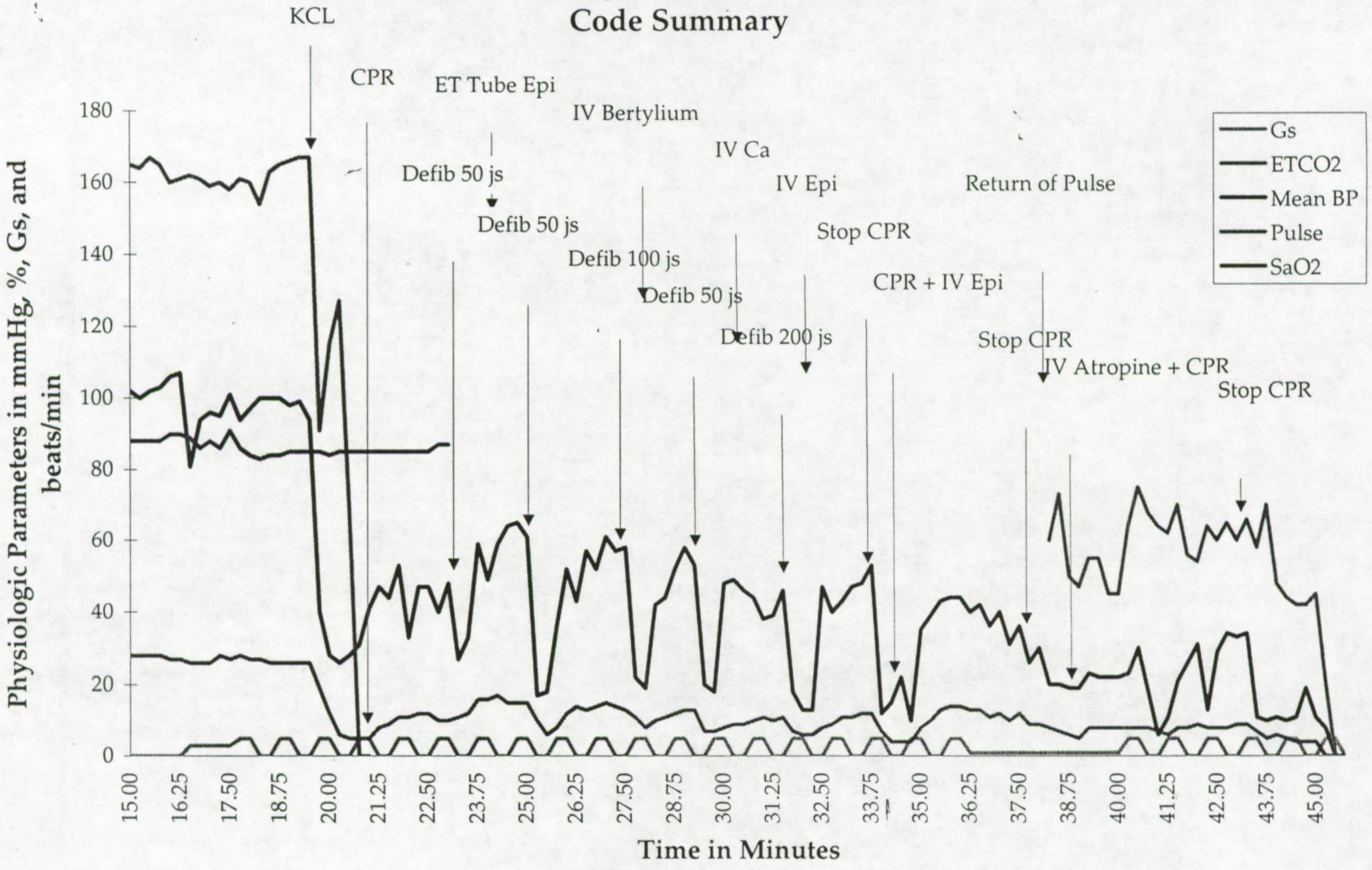

Figure 4: Oxygen Saturation During CPR

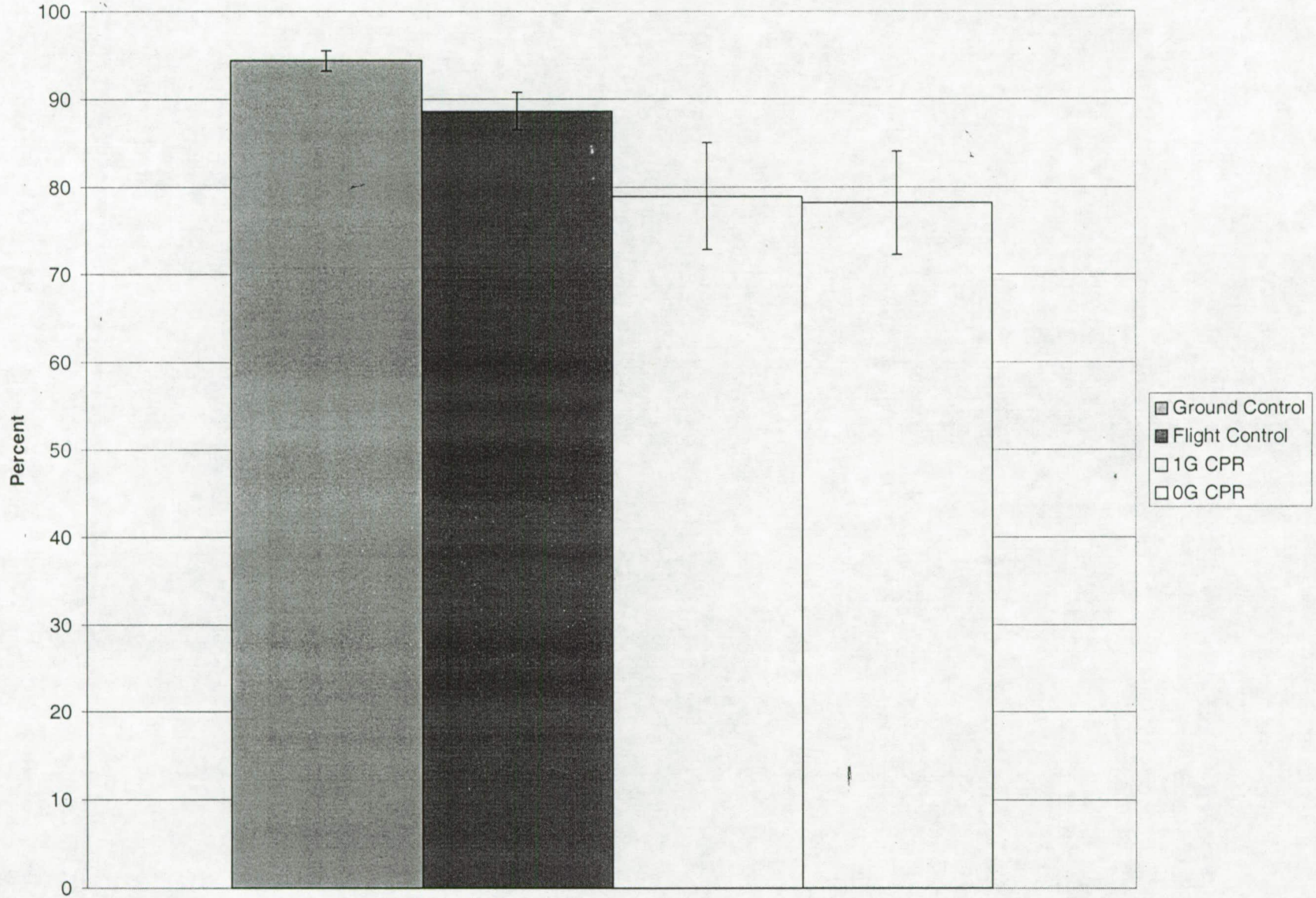

Figure 5: $EtCO_2$ During CPR

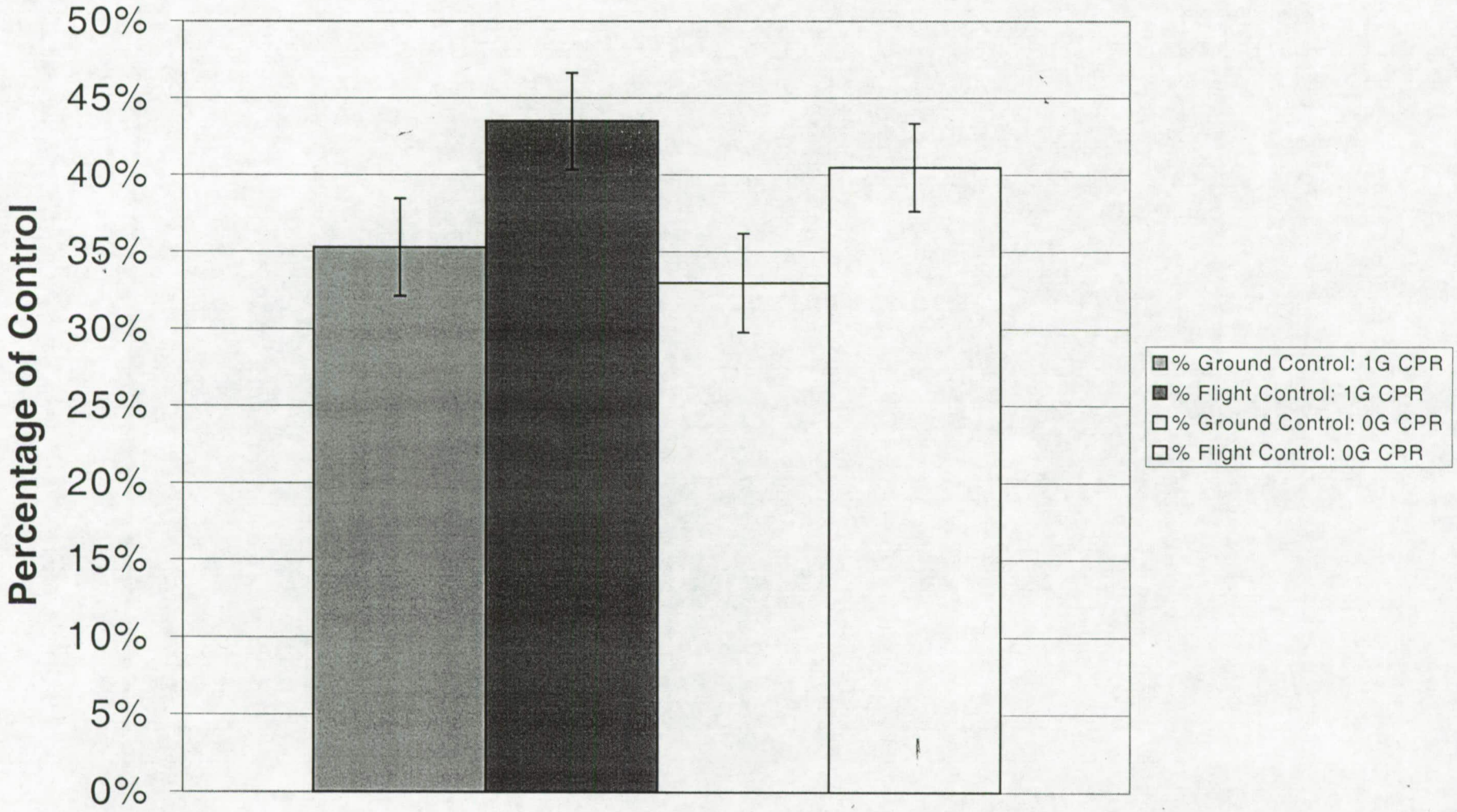

Figure 6: Mean Blood Pressure