THE INFLUENCE OF BLOOD FLOW AND ARTERIAL BLOOD PRESSURE DURING CARDIOPULMONARY BYPASS ON DELTOID MUSCLE GAS TENSIONS AND BODY TEMPERATURE AFTER BYPASS

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SKELETAL MUSCLE OXYGEN (Pm_{O_2}) and carbon dioxide tensions (Pm_{CO_2}) are related to muscle perfusion.¹⁻³ A recent report from this laboratory demonstrated that both high arterial blood pressure and high flow rate are necessary during cardiopulmonary bypass to ensure muscle perfusion and that utilization of pressors during bypass maintains blood pressure at high levels but at the expense of muscle blood flow.⁴ The question of whether it is desirable to perfuse skeletal muscle during extracorporeal circulation could not be answered by that study. The purpose of this study was to determine the influence of skeletal muscle blood flow during bypass on body temperature after bypass and in the early postoperative period.

METHODS

The study was approved by the Wilford Hall U.S.A.F. Medical Center Human Study Committee. Informed written consent was obtained from every patient at the preoperative visit. A total of 24 patients scheduled for coronary artery revascularization operations made up the experimental subjects.

Premedication included pentobarbitone $1 \text{ mg} \cdot \text{kg}^{-1}$ or diazepam $1 \text{ mg} \cdot \text{kg}^{-10}$, morphine $1 \text{ mg} \cdot \text{kg}^{-10}$, and atropine $0.05 \text{ mg} \cdot \text{kg}^{-10}$ given intramuscularly 90 minutes before the scheduled time of operation. Preoperative preparation and intra-operative blood and fluid management schedules have been previously described.^{5,6} Patients were anaesthetized with morphine 1 to $3 \text{ mg} \cdot \text{kg}^{-1}$ plus oxygen and paralyzed with succinylcholine $1.5 \text{ mg} \cdot \text{kg}^{-1}$. The trachea was then intubated and respiration was controlled to maintain Pa_{CO_2} between 4.66–5.32 kPa (35–40 torr) as has been previously described.^{5,6}

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Temperature was measured with oesophageal and rectal probes attached to a Yellow Springs recording module. After induction of anaesthesia a Scientific Research Instrument Corporation Teflon tissue catheter, previously calibrated in lactated Ringer's solution, was implanted into the right or left deltoid muscle through a 12-gauge catheter inserted percutaneously into the muscle. The teflon catheter was attached to a Medspect MN-8 mass spectrometer which continuously sampled and measured muscle oxygen, carbon dioxide and nitrogen tensions.

The cardiopulmonary bypass system consisted of a Bentley BOS-10 bubble oxygenator and Sarns roller pump and was primed with lactated Ringer's solution. Pa_{O_2} was maintained between 19.95–26.6 kPa (150–200 torr) during bypass, Pa_{CO_2} between 4.66–5.32 kPa (35–40 torr) and oesophageal temperature at 28–30° C. Patients were randomly assigned to one of these groups at the time of the preoperative visit. Eight patients (group I) had bypass flow rate adjusted every two to five minutes to keep Pm_{O_2} at pre-bypass values 3.99–4.52 kPa (30–34 torr). Eight patients (group II) had bypass flow rate adjusted to keep mixed venous (common venous return at the entrance to the oxygenator) $P\bar{V}_{O_2}$ between 4.92–5.72 kPa (37–43 torr) (normal values). The final eight patients (group III) had bypass flow adjusted to maintain $P\bar{V}_{O_2}$ between 4.92–4.52 kPa (37–43 torr) but in addition had bypass mean blood pressure increased to 11.97–13.3 kPa (90–100 torr) by a dilute infusion of phenylephrine. No patient received sodium bicarbonate or any other alkali at any time during the investigation.

All patients were warmed through the pump oxygenator to a rectal temperature of 37° C at the end of bypass and maintained on a warming blanket set at 39° C at the end of bypass and in the postoperative recovery unit. Patients were given pure oxygen to breathe after bypass and during the first four hours postoperatively. Pa_{CO_2} was maintained between 4.66–5.59 kPa (35–42 torr) during these times by appropriate alterations in the mechanical respirator. Rectal temperature, Pm_{O_2} , Pm_{CO_2} , Pa_{O_2} , Pa_{CO_2} , arterial CH^+ (pHa) and

TABLE I
RECTAL TEMPERATURE, MUSCLE PO₂ AND PCO₂ AND ARTERIAL BLOOD GASES AND pH BEFORE, DURING AND AFTER BYPASS AND POSTOPERATIVELY IN 24 PATIENTS
(MEAN ± SD)

Flow	Groups	Post-bypass			Post-operatively		
		Pre-bypass	Bypass	30 min.	60 min.	0-2 Hours	2-9 Hours
ml.kg ⁻¹ .min ⁻¹	I II III	— — —	97 ± 8 59 ± 10 58 ± 12	— — —	— — —	— — —	— — —
Mean arterial blood pressure kPa (torr)	I II III	11.44 ± 1.2 (86 ± 9) 11.70 ± 1.06 (88 ± 8) 11.31 ± 1.2 (83 ± 9)	12.77 ± 0.8 (96 ± 6)* 7.98 ± 1.46 (60 ± 11)†§ 12.64 ± 0.27 (95 ± 2)*	10.91 ± 1.60 (82 ± 12) 11.44 ± 1.93 (86 ± 13) 10.77 ± 1.33 (81 ± 10)	10.64 ± 1.2 (80 ± 9) 11.57 ± 1.60 (87 ± 12) 11.17 ± 1.46 (84 ± 11)	11.17 ± 1.33 (84 ± 10) 11.04 ± 1.20 (83 ± 0) 11.31 ± 1.60 (85 ± 12)	10.77 ± 1.33 (81 ± 10) 11.31 ± 1.73 (85 ± 13) 11.04 ± 1.33 (83 ± 10)
Rectal Temperature (degrees C)	I II III	36.2 ± 0.4 36.6 ± 0.5 36.1 ± 0.4	30.9 ± 0.3† 30.3 ± 0.4† 30.7 ± 0.6†	36.5 ± 0.2 34.1 ± 0.5* 34.2 ± 0.6*	36.4 ± 0.2 33.0 ± 0.5†† 32.6 ± 0.5††	37.1 ± 0.4 33.5 ± 0.4†† 33.4 ± 0.7††	37.1 ± 0.4 34.1 ± 0.6†† 34.8 ± 0.7††
Pmco ₂ kPa (torr)	I II III	4.12 ± 0.27 (31 ± 2) 4.12 ± 0.4 (31 ± 3) 3.99 ± 0.27 (30 ± 2)	3.99 ± 0.27 (30 ± 2) 0.40 ± 0.27 (3 ± 2)†§ 1.86 ± 0.53 (14 ± 4)†§	3.72 ± 0.53 (28 ± 4) 2.26 ± 0.53 (17 ± 4)†§ 2.66 ± 0.53 (20 ± 4)†§	3.99 ± 0.40 (30 ± 3) 2.39 ± 0.40 (18 ± 3)†§ 2.93 ± 0.53 (22 ± 4)†§	4.12 ± 0.40 (31 ± 3) 2.66 ± 0.40 (20 ± 3) 3.06 ± 0.04 (23 ± 3)*†	4.12 ± 0.27 (31 ± 2) 3.19 ± 0.27 (24 ± 2)†† 3.46 ± 0.40 (26 ± 3)*
Pmco ₂ kPa (torr)	I II III	6.12 ± 0.40 (46 ± 3) 6.38 ± 0.40 (48 ± 3) 5.99 ± 0.27 (45 ± 2)	5.72 ± 0.27 (43 ± 2) 11.84 ± 0.93 (89 ± 7)†§ 9.71 ± 1.06 (73 ± 8)†§	5.85 ± 0.40 (44 ± 3) 10.51 ± 1.20 (79 ± 9)†§ 8.51 ± 0.80 (64 ± 6)†§	5.99 ± 0.40 (45 ± 3) 10.51 ± 1.20 (79 ± 9)†§ 8.11 ± 0.67 (61 ± 5)†§	6.25 ± 0.53 (47 ± 4) 9.31 ± 0.67 (70 ± 5)†§ 7.71 ± 0.67 (58 ± 5)††	6.12 ± 0.53 (46 ± 4) 8.11 ± 0.80 (61 ± 6)†§ 9.05 ± 0.67 (53 ± 5)††
pH _a	I II III	7.43 ± 0.04 7.44 ± 0.03 7.43 ± 0.04	7.41 ± 0.03 7.42 ± 0.04 7.41 ± 0.04	7.43 ± 0.05 7.40 ± 0.06 7.41 ± 0.05	7.41 ± 0.05 7.39 ± 0.05 7.39 ± 0.05	7.43 ± 0.04 7.36 ± 0.04†† 7.36 ± 0.03††	7.43 ± 0.04 7.37 ± 0.05†† 7.36 ± 0.06††
Base elevations (mmol/l)	I II III	-11 ± 0.4 -1.5 ± 0.6 -0.9 ± 0.4	-0.8 ± 0.2 -1.2 ± 0.4 -1.4 ± 0.5	-1.4 ± 0.3 -1.9 ± 0.21 -2.2 ± 0.6	-1.9 ± 0.4 -2.3 ± 0.8 -2.5 ± 0.9	-1.5 ± 0.4 -4.7 ± 1.1†§ -5.1 ± 1.2†§	-1.3 ± 0.4 -4.3 ± 0.8†† -5.0 ± 0.9††

*P < 0.05, †P < 0.01 Student's paired t-test when compared to pre-bypass values.

††P < 0.05, §P < 0.025 Student's unpaired t-test when compared to Group I values at the same time.

calculated base elevation, using a Severinghaus calculator, were measured before bypass and every 15 minutes during bypass, during the post-bypass operative period, and for four hours post-operatively. Blood gas and pH determinations were made on an Instruments Laboratory blood gas machine and corrections for temperature made using a standard normogram. Values for all variables were averaged* every 30 minutes during and after bypass and every two hours post-operatively. Data were evaluated for statistical significance utilizing Student's paired and unpaired t-tests.

RESULTS

Mean doses of morphine, arterial blood pressure, cardiac output, rectal and oesophageal temperatures, muscle and arterial gas tensions and arterial pH and calculated base elevation were similar in the three groups immediately before bypass. Groups I and III had significantly higher and group II lower mean arterial blood pressures during bypass than during the pre-bypass period (Table I). P_{aCO_2} , pH_a and calculated base deficit were similar in the three groups during bypass and not significantly different than pre-bypass values. P_{aO_2} and rectal and oesophageal temperatures were also similar in the three groups during bypass but significantly lower than pre-bypass values.

Pm_{O_2} and Pm_{CO_2} were not significantly different from pre-bypass values at any time during the study in group I. Pm_{O_2} was markedly reduced and Pm_{CO_2} increased during bypass, the post-bypass period and up to four hours postoperatively in groups II and III. After rewarming to 37° at the end of bypass, rectal and oesophageal temperatures decreased and remained reduced for up to four hours postoperatively in groups II and III. In contrast, rectal and oesophageal temperatures in group I did not significantly change after bypass or postoperatively. P_{aO_2} and P_{aCO_2} were similar in the three groups during the post-bypass period and up to four hours postoperatively. Arterial pH and base elevation were also similar in the three groups after bypass but were significantly lower in groups II and III than group I in the postoperative period.

*Statistical significance for pH changes were determined by converting pH to concentrations of hydrogen ion and then reconvert to pH after mean, standard deviation, P values, etc., were determined.

DISCUSSION

Flow rates and arterial blood pressures considered ideal during cardiopulmonary bypass vary a great deal from one cardiopulmonary bypass team to another.* A few years ago we demonstrated that regulating bypass flow rate to ensure a normal mixed venous oxygen tension ($P\bar{V}_{O_2}$) was superior to perfusing at a fixed calculated flow rate based on body surface or weight.⁷ In a recent study we showed that regulation of flow rate during cardiopulmonary bypass to maintain a normal $P\bar{V}_{O_2}$ produced normal arterial and mixed venous pH but did not ensure a normal Pm_{O_2} and thus normal perfusion to muscle.⁴ The data in that study indicated that both high arterial pressure and flow rate were necessary during bypass to maintain normal muscle perfusion and that utilization of pressors during bypass maintained high mean arterial blood pressure but at the expense of muscle blood flow. Whether it is desirable to perfuse skeletal muscle during non-pulsatile extracorporeal circulation could not be answered by our previous report. The results of this study demonstrate that skeletal muscle perfusion during bypass prevents decreases in body temperature after end-of-bypass rewarming and avoids impaired skeletal muscle blood flow in the post-bypass and early postoperative periods. Our findings also suggest that skeletal muscle perfusion during bypass decreases the amount of acid metabolites present in the circulation postoperatively.

Although cooling during bypass decreases metabolic and perfusion requirements, it is clear from the marked increases in Pm_{CO_2} measured in patients in groups II and III in this study, that some skeletal muscle metabolism continues. Absence of marked decreases in perfusion to muscle during and after bypass requires that the acid metabolites produced during these periods will accumulate. Removal of these metabolites will only occur after circulation to muscle is re-established in the post-bypass and post-operative periods. This was undoubtedly the mechanism which resulted in post-operative decreases in pH and base elevation in our patients in groups II and III. While the modest decreases in pH and base elevation observed post-operatively in patients in groups II and III did not appear to have a significant effect on their recovery, this may not be the case in patients with unstable circulatory dynamics. Metabolic acidosis significantly de-

*Garman JK, personal communication.

creases myocardial inotropy⁸ and could, even in small amounts, result in cardiovascular decompensation in a patient with marginal myocardial mechanics or cardiovascular dynamics.

Decreases in body temperature after bypass and in the early postoperative period in spite of body surface warming are a common problem and can result in depressed respiratory and circulatory dynamics and increased cardiac instability.^{9,10} Our findings in this study suggest that cooling after bypass rewarming may primarily be caused by poor perfusion to, and thus inadequate rewarming of, skeletal muscle at the end of extracorporeal circulation. The use of high flows and arterial pressures (without resorting to vasopressors) ensured skeletal muscle perfusion during bypass and eliminated post-bypass and postoperative cooling. While employment of high pressure and high flow bypass techniques have been criticized because of increased haemolysis, high urine output (and thus electrolyte loss) and risk of particulate and air embolism,¹¹ these have not been problems in our hospital. Therefore, high flow-high arterial pressure bypass appears to be a simple technique for avoiding post-bypass and post-operative hypothermia.

SUMMARY

The results of this study demonstrate that skeletal muscle perfusion during bypass requires high flows and mean arterial pressures and that use of vasopressors during bypass impairs skeletal muscle blood flow. Our findings also indicate that skeletal muscle perfusion during bypass decreases metabolic acidosis after operation and prevents decreases in body temperature and poor skeletal muscle blood flow in the post-bypass and early postoperative periods. Our results suggest that perfusing to maintain normal Pm_{O_2} during extracorporeal circulation is superior to more conventional techniques of conducting bypass.

RÉSUMÉ

Nous avons étudié l'influence du débit sanguin musculaire durant la circulation extracorporelle sur la température des opérés après la CEC et au cours des premières heures post-opératoires. La circulation musculaire était évaluée par la mesure de la PO_2 et de la PCO_2 au niveau du deltoïde.

Dans un premier groupe de huit malades, le débit de la CEC a été ajusté de façon à maintenir la PO_2 du deltoïde (Pm_{O_2}) aux valeurs observées

avant la CEC, soit 3.9 à 4.5 kPa (30–34 torr). Chez huit autres patients (groupe II), le débit de CEC a été ajusté de façon à maintenir la PO_2 veineuse mixte (Pv_{O_2}) aux valeurs observées avant la CEC, soit entre 4.92 et 5.72 kPa (37–43 torr). Enfin, un dernier groupe de huit malades (groupe III) a été perfusé comme les patients du groupe II et, en plus, une perfusion de phényléphrine a été utilisée chez eux pour maintenir la pression de perfusion entre 11.9 et 13.3 kPa (90 à 100 torr). En cours de CEC, les malades ont été refroidis à une température œsophagienne entre 28° et 30° C; ils ont tous été réchauffés à une température rectale de 37° C en fin de CEC.

La pression artérielle moyenne, le débit cardiaque, les températures rectales et œsophagiennes, ainsi que les gazométries et les pH artériels et musculaires, étaient comparables chez les malades des trois groupes avant la circulation extracorporelle. La Pa_{O_2} , la Pa_{CO_2} , la pHa , l'excès de base calculé, ainsi que les températures rectales et œsophagiennes étaient similaires chez les malades des trois groupes en cours de CEC, mais les patients des groupes I et III avaient une pression de perfusion significativement plus élevée que ceux du groupe II. La tension de la PO_2 et de la PCO_2 au niveau du deltoïde (Pm_{O_2} et Pm_{CO_2}) étaient semblables à celles observées avant la CEC au cours de toute la durée de l'étude chez les malades du groupe I. La Pm_{O_2} était significativement abaissée, et la Pm_{CO_2} significativement élevée durant et immédiatement après la CEC, et au cours des quatre premières heures d'observation post-opératoire chez les patients des groupes II et III. Après le réchauffement à 37° C, en fin de CEC, les températures rectales et œsophagiennes ont diminué et sont demeurées plus basses jusqu'à quatre heures après la fin de la chirurgie chez les patients des groupes II et III; par contre, les températures rectales et œsophagiennes n'ont pas changé de façon significative après la CEC et dans la période post-opératoire immédiate chez les malades du groupe I. Le CH^+ (pH) et l'excès de base artériels étaient semblables dans les trois groupes à la fin de la CEC, mais étaient significativement plus bas dans la phase post-opératoire chez les malades des groupes II et III.

Les résultats de nos travaux démontrent que le maintien d'une bonne perfusion musculaire en cours de circulation extracorporelle prévient les chutes de température observées après le réchauffement de fin de CEC et prévient l'insuffisance circulatoire dans les masses mus-

culaires après la CEC et au cours de la phase post-opératoire. Nos observations suggèrent également que la perfusion adéquate des masses musculaires en cours de CEC diminue la quantité de métabolites acides présents dans la circulation durant la phase post-opératoire.

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