WHOLE-BODY METABOLISM DURING AND AFTER OPEN-HEART SURGERY

EMERSON A. MOFFITT, M.D.,* SAIT TARHAN, M.D., AND DWIGHT C. MCGOON, M.D.

ACROSS-THE-HEART arteriovenous differences in energy substrates and electrolytes of patients undergoing whole-body perfusion for cardiac surgery have been reported.¹⁻³ Arteriovenous differences across the whole body of patients undergoing abdominal operations also have been investigated.⁴ To assess the effects, during severe stress, of perfusion and cardiac operation, we examined the arterial and venous blood levels of substrates, electrolytes, oxygen, and acid-base variables in 11 patients.

MATERIALS AND METHODS

Patients Studied. – The clinical and cardiac data of the 11 patients are listed in Table I. Four of the 11 patients had had previous cardiac operations, either open or closed.

Study Protocol. – An arterial sample was taken before induction of anesthesia with the patient breathing air (Table II). At subsequent sample times, simultaneous right atrial and arterial blood was drawn during operation and perfusion and twice daily for three days after operation. Five patients were studied during the operation, and six entered the study during the postoperative period.

Analytical methods were as previously described.¹⁻³ The samples were iced, and blood gases were determined within ten minutes by appropriate electrodes at 37° C. A correction was made when blood temperature was below 36° C. Oxygen content was calculated from the haemoglobin concentration and its oxygen saturation; buffer base was read from the Singer-Hastings nomogram.⁵ Plasma osmolality and total calcium and sodium, potassium, chloride, and inorganic phosphate were determined. Energy substrates measured in blood were glucose, nonesterified fatty acids (NEFA), total ketone bodies, lactate, and pyruvate.

Paired data of arterial and venous concentrations at each sample time were compared using the Student t-test. Using unpaired data analysis, arterial and venous concentrations at each sample time were compared to those of general surgical patients in a previous study.⁴ At each sample time, variables of the right atrial blood were compared with those of the coronary sinus blood of patients having aortic replacements.¹

Anaesthetic and Surgical Methods. – All patients had nitrous oxide-halothane anaesthesia with small increments of succinylcholine. Ten patients were awake and

*Present address: Department of Anaesthesia, Dalhousie University Medical School, Halifax, Nova Scotia.
Mayo Clinic and Mayo Foundation
Rochester, Minnesota

TABLE I
CLINICAL AND CARDIAC DATA ON 11 PATIENTS
WHO UNDERWENT OPEN-HEART SURGERY

<i>Sex</i>	
Males	4
Females	7
Age, yr	52.8 (30-71)*
Weight, lb	139 (91-183)
Surface area, m ²	1.71 (1.44-2.04)
Patients' class (NYHA)	
II	2
III	5
IV	4
<i>Operation</i>	
Aortic replacement	5
Mitral replacement	4
Mitral annuloplasty	1
Triple-valve replacement†	1
Perfusion time, min	85 (66-162)
<i>Patients</i>	
On digitalis	8
Ondiuretics	6

*Mean (range).

†Aortic, mitral, and tricuspid.

TABLE II
SCHEDULE SEQUENCE OF BLOOD SAMPLING

Sample	Time
1	Before induction of anesthesia*
2	Before perfusion from both patient and priming solution
3	After ten minutes of perfusion
4	Before beginning rewarming patient to 36° C
5	End of perfusion
6	One-half hour after perfusion
7	End of operation
8	Two hours after operation
9	Day 2 - 8 a.m.
10	Day 2 - 3 p.m.
11	Day 3 - 8 a.m.
12	Day 3 - 3 p.m.
13	Day 4 - 8 a.m.
14	Day 4 - 3 p.m.

*Sample 1 was arterial; both arterial blood and right atrial blood were drawn at all other sample times.

extubated at the end of operation, while the one patient with triple valve replacement had assisted respiration through a tracheal tube overnight. One patient was re-explored three hours after operation because of persistent bleeding. All 11 patients survived and were dismissed from the hospital.

Perfusions were at 30° C with the Mayo-Gibbon vertical-sheet oxygenator primed with diluted acid-citrate-dextrose blood. The diluents per 500 ml of blood were 150 ml of 5 per cent dextrose in 0.45 per cent NaCl, 65 ml of 0.3M tris(hydroxymethyl)aminomethane (THAM), 4 mEq of KCl, 500 mg of CaCl₂, and 3,000 units of heparin. Approximately 250 ml of 5 per cent dextrose in water was given intravenously during operation. All prostheses were of the Starr-Edwards type. Both coronary arteries were directly perfused in patients with aortic replacement. The mean duration of perfusion was 85 minutes (range 66 to 162).

FIGURE 1. Whole-body oxygenation. Venous oxygen content is elevated during hypothermic perfusion.

RESULTS

Mean concentrations of the variables measured in arterial and right atrial blood are shown in Figures 1 through 7. Buffer base was greater in venous than in arterial blood half an hour after perfusion and on the morning of days 2 and 4. There were isolated differences between arterial and venous levels: venous sodium was higher at the end of operation, venous osmolality was higher on the afternoon of day 2, and arterial potassium was higher at the end of operation and two hours after it. Venous pyruvate was lower than arterial pyruvate before perfusion and was higher on the afternoon of day 3. NEFA were lower in venous than in arterial blood half an hour after perfusion, at the end of operation, on day 3, and on the morning of day 4.

Comparisons between right atrial blood of this group of patients undergoing cardiac operations with perfusion and a group of patients undergoing general abdominal surgery⁴ are shown in Table III. The differences in concentrations between right atrial blood in the present series and coronary sinus blood of ten patients perfused and managed in similar manner for aortic valve replacement¹ are listed in Table IV.

DISCUSSION

The arterial concentrations of oxygen, acid-base parameters, electrolytes, and energy substrates followed the patterns previously documented.¹⁻³ Oxygenation is adequate in the presence of an increased inspired concentration. Alkalosis is

FIGURE 2. Acid-base balance. Usual increase in carbon dioxide and decrease in pH are seen as blood traverses peripheral tissues.

TABLE III
COMPARISONS OF RIGHT ATRIAL BLOOD IN OPEN-CARDIAC GROUP
VERSUS ABDOMINAL SURGICAL GROUP

Variable	Cardiac group	
	Greater than abdominal group	Less than abdominal group
PO_2	—	Preperfusion, day 3, p.m.
O_2 saturation	—	End of operation, day 3, p.m.
Hct	End of operation, day 4, p.m.	—
PCO_2	End of operation, day 4, p.m.	—
pH	—	End of operation, day 3, p.m.
Total Ca	Throughout, except day 4, p.m.	—
Na	—	Day 4, p.m.
K	During perfusion	—
Glucose	End of operation	—
Lactate	End of operation, 2 hr postop.	—
Pyruvate	Throughout	—
NEFA	Preperfusion, day 2, p.m.	End of operation
Ketone bodies	—	End of operation

FIGURE 3. Electrolytes. During operation, plasma sodium decreases because of dilution. Both sodium and osmolality decrease after operation.

present almost throughout, respiratory in nature during anaesthesia, and with a metabolic component after the operation. With both potassium and calcium added to the priming solution elevated plasma levels of both ions are seen during operation, while potassium levels become subnormal in the early postoperative hours. Values for plasma osmolality, sodium, chloride, and inorganic phosphate all become subnormal by the fourth postoperative day, most likely from intravascular water retention. The metabolism of the large glucose load given with this haemodiluted priming solution is at least partly responsible for the increases in the levels of lactate and pyruvate that occur. Arterial concentrations of both fatty acids and ketone bodies are elevated throughout, except for several hours at the end of operation when the plasma insulin level is known to be elevated.³ This elevation of the elements involved in lipid metabolism indicates the severe stress to which these people are subjected, as seen also by an increase in growth hormone activity.³

Whole-Body Arteriovenous Differences.—The usual decreases in oxygen concentration and pH, with increase in carbon dioxide, are seen as blood traverses the peripheral tissues. The constancy of these arteriovenous differences is apparent from the figures, as both blood levels rise and fall in parallel from sample time to sample time. An exception to this is during perfusion at 30° C when oxygen consumption and carbon dioxide production decrease. Mean levels of oxygen tension

FIGURE 4. Electrolytes. Plasma potassium and calcium are elevated during operation because of extra amounts in priming solution; phosphate level rises on day 2.

FIGURE 5. Glucose metabolism. Large glucose load in priming solution causes high blood levels during operative day.

FIGURE 6. Energy metabolism. Both lactate and pyruvate increase greatly during operation, partly from metabolism of glucose.

FIGURE 7. Lipid metabolism. Body depends heavily on lipids during all 4 days, as evidenced by elevated levels of fatty acids and ketone bodies.

TABLE IV
COMPARISON OF RIGHT ATRIAL-TO-CORONARY SINUS BLOOD IN OPEN-CARDIAC GROUP
VERSUS AORTIC REPLACEMENT GROUP

Variable	Right atrial blood	
	Less than coronary sinus blood	Greater than coronary sinus blood
P _O ₂	—	All times except early and midperfusion
O ₂ content	—	All times except during perfusion, day 2, p.m., and day 3, a.m.
O ₂ saturation	—	All except during perfusion
pH	—	Preperfusion, early perfusion, ½-hour postperfusion
Na	Preperfusion, early perfusion	—
Osmolality	Preperfusion, midperfusion, ½-hour postperfusion, 2-hour postop.	—
K	—	Preperfusion
Total Ca	Day 4, p.m.	—
Pyruvate	—	End of operation, 2-hour postop.
NEFA	—	Day 2, a.m., day 3, a.m.

in right atrial blood remained between 30 and 35 torr after operation, with mean arterial oxygen tension staying above 100 torr.

Differences between arterial and right atrial levels of electrolytes were not significant, except for potassium at the end of operation and two hours later. At these times, the arterial concentration of potassium has decreased below normal. With potassium disappearing rapidly from the arterial blood through the kidneys, and likely into cells under the influence of an elevated plasma insulin,⁶ a lower potassium concentration could be seen in venous than in arterial blood. The increased insulin activity at this time accounts for the decrease in fatty acids to normal range⁷ but not for the significantly lower venous concentration then present. This smaller amount of fatty acids in venous blood also occurs on the third and fourth days after operation, when the body is depending heavily on lipid for energy production, as mirrored in the elevated ketone concentrations in blood.

Venous Levels of Variables in Abdominal Versus Cardiac Operations. — Most of the differences in venous blood between the two kinds of operations are due to imposition of the period of whole-body perfusion and the greater degree of stress in the cardiac patient. The glucose of the priming solution accounts for the elevation of glucose, lactate and pyruvate levels in cardiac patients. In the same group, more severe emotional stress can account for the higher fatty acid levels before perfusion⁸ and on the second day.⁹ Lower fatty acid and ketone body concentrations at the end of operation in cardiac patients can be explained by suppression of lipid mobilization by elevated insulin activity.⁷ Differences in calcium and potassium levels were produced by the amounts added in the priming solution. Both oxygen tension and saturation were lower in cardiac patients than in general surgical patients during operation and on the third day. This is likely due to the greater degree of intrapulmonary shunting and lower cardiac output present in the more seriously ill cardiac patient.¹⁰

Right Atrial Versus Coronary Sinus Blood Variables in Open-Heart Operations. — The two groups of patients were perfused and managed similarly, and no differ-

ences in arterial levels of variables were seen. The greater extraction of oxygen from blood traversing the myocardium, compared to the whole body, is seen from the lower oxygen tension and content of coronary sinus blood. This difference was abolished during hypothermic perfusion with the heart not performing its usual work. The only difference in acid-base was that coronary sinus blood was more acidic before perfusion, early during perfusion, and shortly after perfusion. Osmolality was consistently lower in right atrial than in coronary sinus blood from before perfusion through two hours after operation. This occurred without differences in calcium or potassium levels and with lower sodium concentration before and early during perfusion. One explanation could be that the myocardium was taking up water during and after perfusion.

Two differences are seen between the behaviour of myocardial and whole-body energy substrates. Right atrial blood had higher pyruvate concentrations near the end of operation. The whole body likely produced more pyruvate than did the myocardium in the metabolism of the extra glucose given. Fatty acid levels were higher in blood from the whole body than in that from the heart on the morning of both the second and third days. With equal amounts of fatty acid per unit volume of arterial blood, greater extraction by the myocardium would account for less in the blood from the coronary sinus. Fatty acids are the major substrate for myocardial energy, especially with inadequate amounts of glucose available.¹¹

SUMMARY

Serial samplings of arterial and right atrial blood were done in 11 adult patients before, during, and after open-heart surgery. Fatty acid levels of venous blood were higher for cardiac surgical patients than for general surgical patients; more severe stress of the cardiac patients can account for this difference. Oxygen tension and saturation were lower in cardiac patients during operation and on the third day, the decrease being most likely due to greater degrees of pulmonary shunting and lower cardiac outputs of this group of patients. Two differences were seen between the behaviour of myocardial and whole-body energy substrates: (1) pyruvate concentrations were higher in right atrial blood than in coronary sinus blood at the end of surgery, indicating that the whole body produced more pyruvates than the myocardium did in the metabolism of the glucose load; and (2) fatty acid levels were higher in right atrial blood than in coronary sinus blood on the morning of the second and third postoperative days, indicating the greater degree of extraction of fatty acids by the myocardium, fatty acids being major substrates for myocardial energy.

RÉSUMÉ

Au cours de la chirurgie à cœur ouvert, chez 11 adultes, nous avons fait en série des échantillonnages de sang artériel et de l'oreillette droite avant, durant et après l'opération. Les taux d'acides gras du sang veineux étaient plus élevés pour les malades en chirurgie cardiaque que pour les malades en chirurgie générale; une plus grande agression pour les malades cardiaques peut être responsable de cette

différence. La tension d'oxygène et la saturation étaient plus basses chez les malades cardiaques au cours de l'opération et le troisième jour postopératoire, la diminution étant due, vraisemblablement, à des degrés plus importants de dérivation (shunting) et à des débits cardiaques plus bas chez le groupe de cardiaques. Nous avons observé deux différences entre le porteur de troubles myocardiques et les substrats énergétiques de tout l'organisme : 1) Les concentrations de pyruvates étaient plus élevées dans le sang de l'oreillette droite que dans le sang du sinus coronarien à la fin de la chirurgie, indiquant que l'organisme entier produit plus de pyruvates que ne le fait le myocarde dans le métabolisme de la masse de glucose; et 2) les taux d'acides gras étaient plus élevés dans le sang de l'oreillette droite que dans le sang du sinus coronarien le matin de l'opération, le deuxième et le troisième jours postopératoires, indiquant un plus fort degré d'extraction d'acides gras par le myocarde, acides gras qui sont les principaux substrats énergétiques du myocarde.

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