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## METABOLIC CHANGES IN THE UPPER LIMB DURING TOURNIQUET ISCHAEMIA

*A Clinical Study*

*By*

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A bloodless field is essential in surgery of the upper limb. But there are risks involved in maintaining it, the greatest of which is probably ischaemia of unduly long duration. Some workers attribute so-called tourniquet paralysis to ischaemia (*Bentley & Schlapp* 1943, *Déry, Pelletier, Jacques, Clavet & Houde* 1965). All tissues doubtless suffer from ischaemia, which actually represents the beginning of tissue death. *Negovskii* (1962) established a metabolic condition similar to that occurring in an ischaemic limb in the blood of patients in terminal states or during clinical death. The tissue changes are best studied in histologic specimens, but it is only exceptionally possibly to obtain such material *in vivo* without harm to the patient. Capillary blood is in metabolic equilibrium with the tissue in question, especially when the blood flow is stopped. In such circumstances, blood taken from a vein behind the capillary bed obviously possesses the same properties as capillary blood. This being the case, it is possible to elucidate metabolic phenomena of the tissues by means of certain haematologic studies. The purpose of the present work was to study the metabolic changes demonstrable in the blood after varying periods of ischaemia in connection with operations on the upper limb.

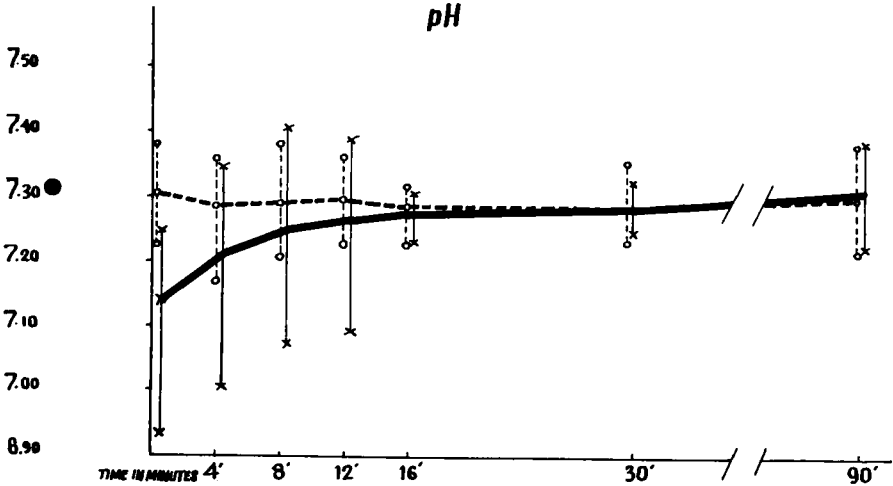
### MATERIAL AND METHOD

The series comprised 20 patients, aged 13-58, mean age 28.5 years. A reconstructive operation of the hand of varying duration was performed on all the patients. The duration of ischaemia was 35-155 min., mean 99 min.

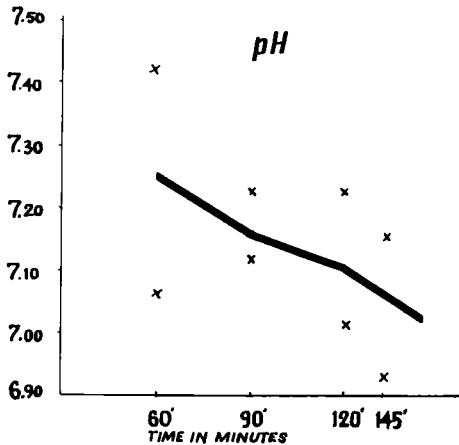
*A common note:*

In the tables the solid line represents the average values for the limb kept in ischaemia, the dotted line the average values for the intact limb. The vertical lines show the deviation of determinations. The black spot on the left indicates the average of determinations before the beginning of anaesthesia.

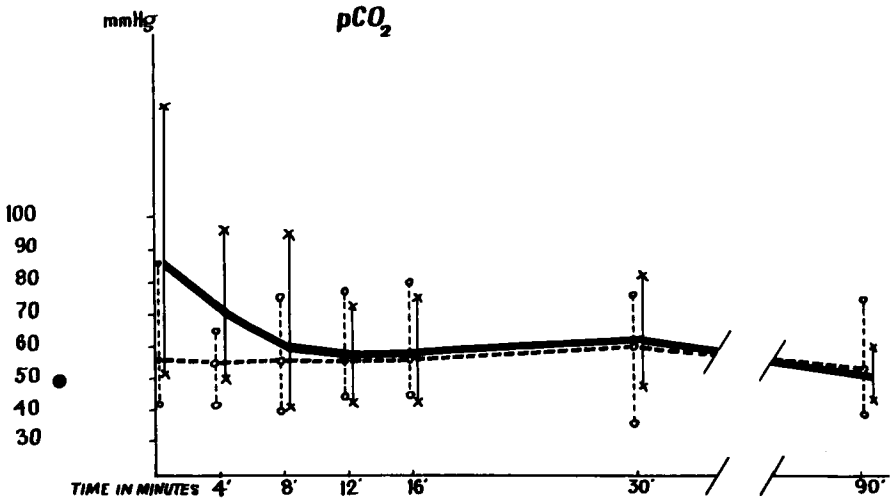
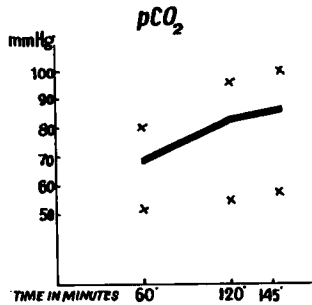
*Table 1. pH determinations after opening the tourniquet.*



*Table 2. pH as a function of the duration of ischaemia (the operated limb).*



The anaesthesia given in 15 cases was combined thiopentone-halothane-nitrous oxide. The patients were intubated but breathed spontaneously. The oxygen content of the anaesthetic gas mixture was 37 per cent. The patients' acid-base balance was normal during surgery before the tourniquet was opened.

Table 3.  $p\text{CO}_2$  determinations after opening the tourniquet.Table 4.  $p\text{CO}_2$  as a function of the duration of ischaemia (the operated limb).

Five patients were operated under plexus anaesthesia.

Neither the temperature of the operated limb nor that of the patient was measured during the operation.

The following determinations were made: acidity (pH),  $\text{PCO}_2$ , standard bicarbonate, base excess (BE),  $\text{pO}_2$ , potassium, pyruvic acid, lactic acid, creatine phosphokinase (CPK). Blood specimens were taken from the cubital vein or the forearm vein, both from the operated and from the contralateral arm in a following series:

1. 5 ml was drawn into a heparinised syringe for blood gas analysis, care being taken that no air entered the syringe.
2. 10 ml was drawn into three separate tubes for determination:
  - a. of potassium,
  - b. of lactic and pyruvic acid; proteins were precipitated with perchloric acid immediately after taking the sample; and
  - c. of CPK.

Table 5. Standard bicarbonate determinations after opening the tourniquet.

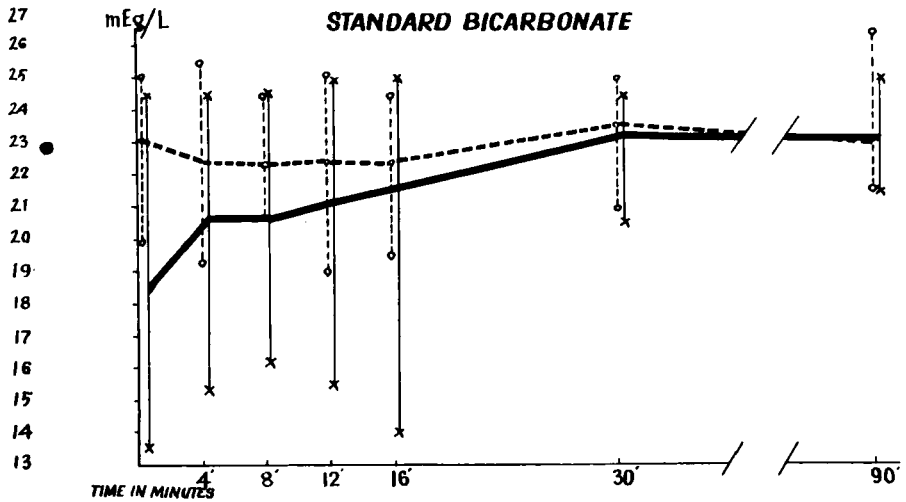
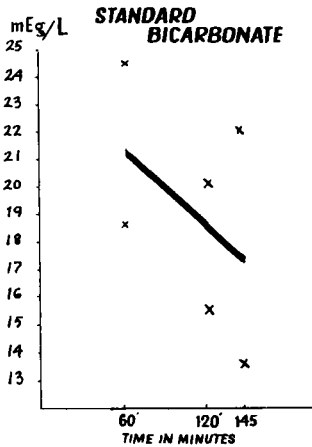


Table 6. Standard bicarbonate as a function of the duration of ischaemia (the operated limb).



The series of samples were taken at the following times:

1. from the healthy upper limb only before anaesthesia. All the following samples were taken simultaneously from both upper limbs.
2. immediately after the opening of the tourniquet.
3. 4 min. later (4').
4. 4 min. later (8').
5. 4 min. later (12').
6. 4 min. later (16').

Table 7. Base excess determinations after opening the tourniquet.

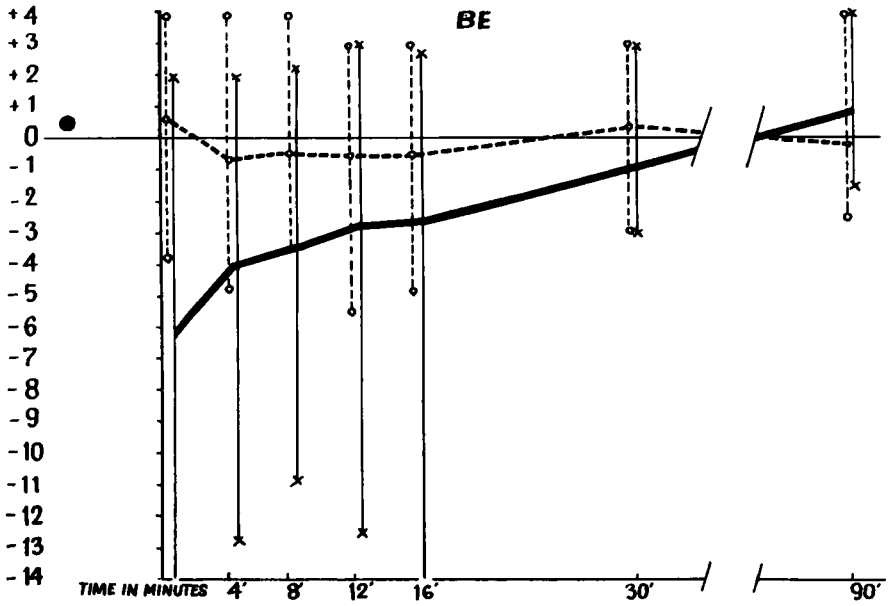


Table 8. Base excess value as a function of the duration of ischaemia (the operated limb).

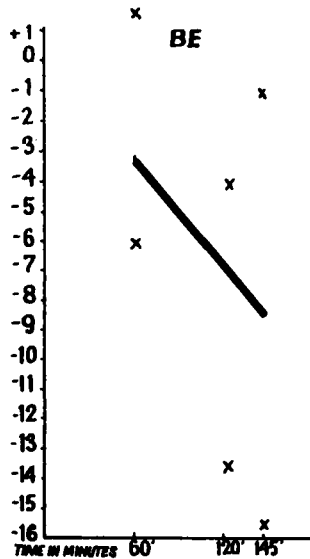


Table 9.  $pO_2$  determinations after opening the tourniquet. The double line represents the average values for patients under plexus anaesthesia (the operated limb).

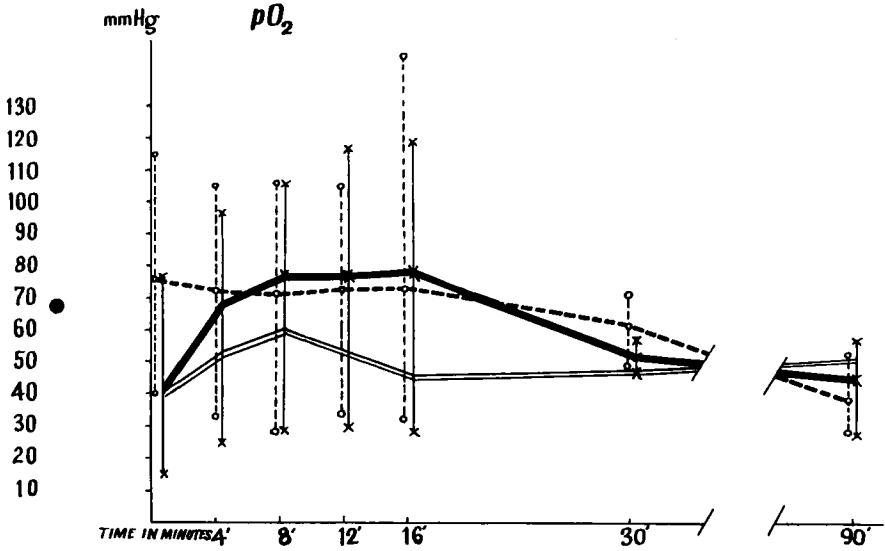
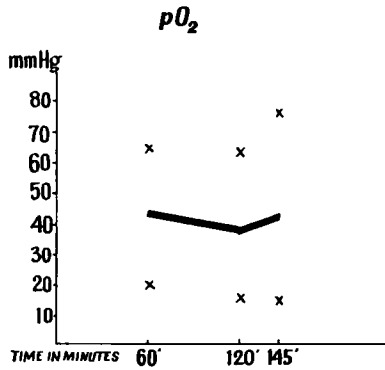


Table 10.  $pO_2$  values for the upper limb kept in ischaemia correlated with the duration of ischaemia.



7. 14 min. later (30').

8. 60 min. later, i.e. 90 min. after opening the tourniquet (90').

The time of sampling was recorded. It was impossible to avoid small deviations from the timetable.

The laboratory tests were performed by the following methods:

Blood pH,  $pCO_2$ , standard bicarbonate and base excess were measured in the blood pH-meter devised by Astrup *et al.* (1960).

Table 11. Lactate determinations after opening the tourniquet.

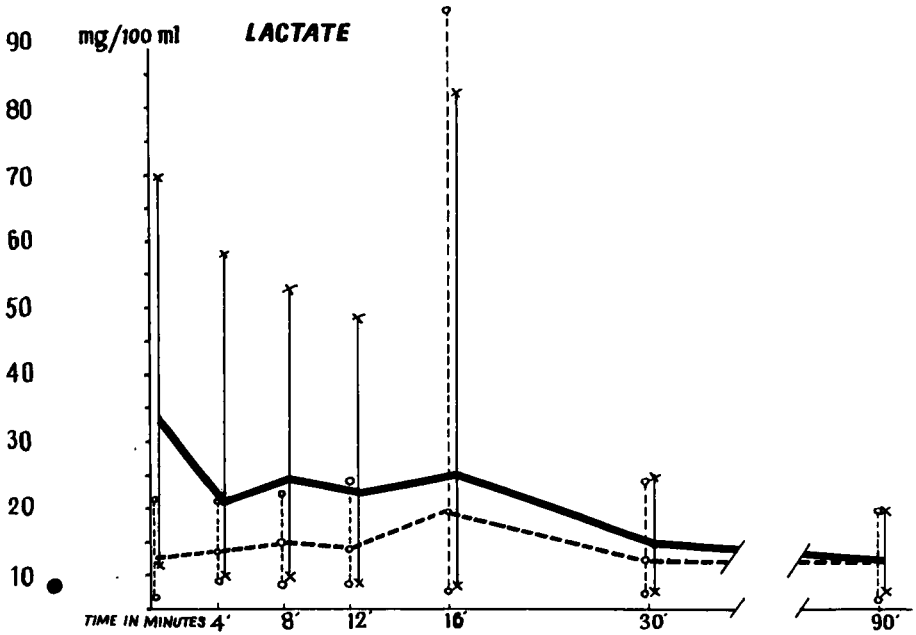
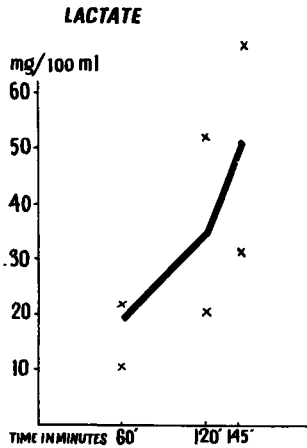


Table 12. Lactate concentration as a function of the duration of ischaemia (the operated limb).



An oxygen electrode was used for the  $pO_2$  measurements (Radiometer 1963). Lactate, pyruvate and creatine-phosphokinase were measured by the enzymatic method (Biochemia "Boehringer" 1961-1965).

An EEL flame photometer was used for the determination of potassium.

The results are given in Tables 1-16.

Table 13. Pyruvate determinations after opening the tourniquet.

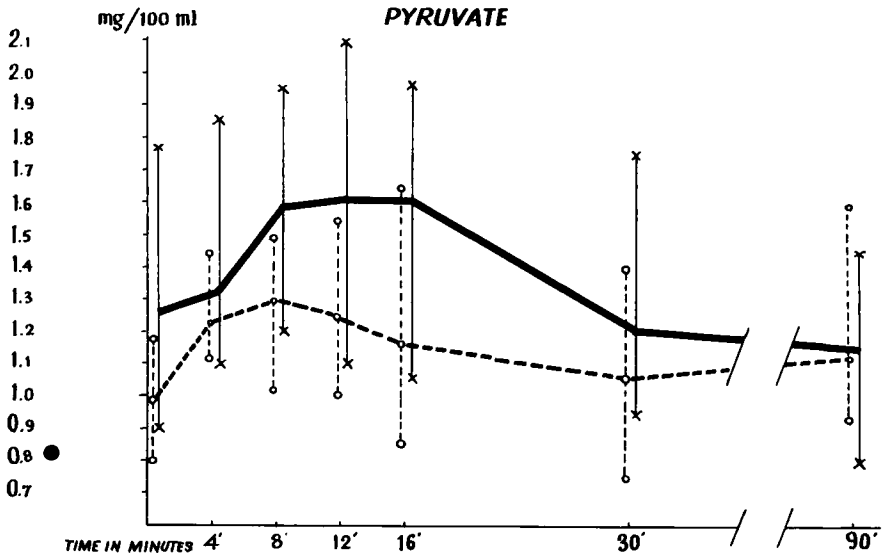
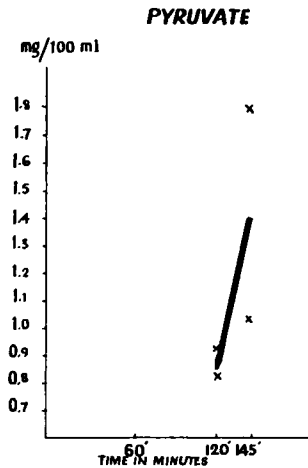


Table 14. Pyruvate as a function of the duration of ischaemia (operated limb).



DISCUSSION

Although the pH was distinctly lowered, its mean minimum, 7.14, was not particularly low. The normal pH of venous blood is 7.30-7.40 (Thorén 1960). The pH value may fall much lower in some pathologic conditions (Siggaard-Andersen 1963). Acidity may reach the level of

Table 15. Potassium determinations after opening the tourniquet.

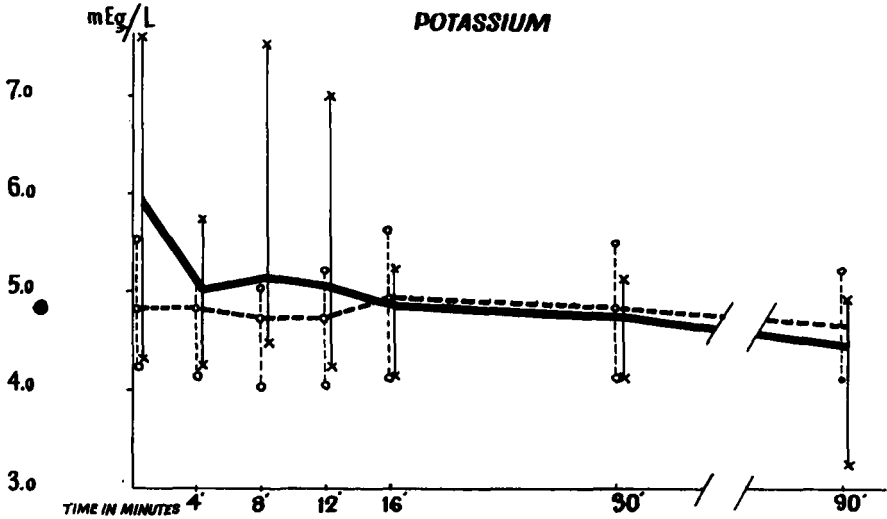
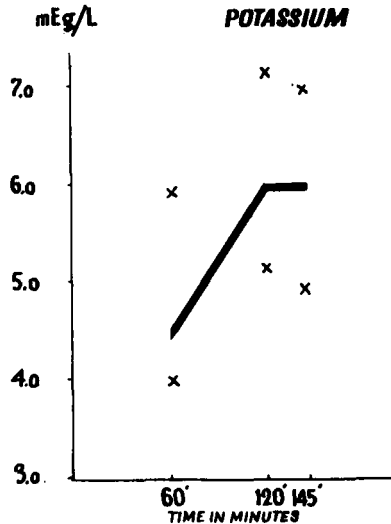


Table 16. Potassium values in correlation with the duration of ischaemia.



the intact limb in 16 min. The organism is thus well able to compensate the drop in the pH level following the opening of the tourniquet. When the duration of ischaemia is prolonged, the pH declines almost linearly. It falls to close to 7.0 during ischaemia of over 2 hours. This pH value is nearly the same as the intracellular pH (Bittar 1964).

The change in  $p\text{CO}_2$  is not great for the length of the ischaemic periods, though the mean, 85 mm Hg, is acidotic. Elevation of the  $p\text{CO}_2$  value as a function of the ischaemic period is not steep. The  $p\text{CO}_2$  may rise to over 150 mm Hg in some pathologic conditions (*Siggaard-Andersen*), and therefore the values in the present study cannot be regarded as very high.

Metabolic acidosis according to the standard bicarbonate and base excess values is not pronounced, but its neutralisation is slower than the normalisation of  $p\text{CO}_2$ . This is because the elimination of acid metabolites takes longer than the diffusion of  $\text{CO}_2$  from tissues to blood. BE values of about  $-30$  are measured in certain acidotic conditions (*Siggaard-Andersen*) and the lowest mean,  $-6.1$ , of our measurements was thus not very low.

The partial pressure of oxygen does not drop as a function of time. The processes which take place in an ischaemic limb after more than one hour are obviously partly anaerobic. Considerable dissociation of oxygen of myoglobin occurs only after the  $p\text{O}_2$  has fallen below 10 mm Hg. Obviously, some such situation has prevailed during ischaemia. However, the oxygen stores of myoglobin are not appreciably depleted, judging by the  $p\text{O}_2$  values. The percentage dissociation of myoglobin when  $p\text{O}_2$  is 40 is about 90 and there is consequently considerable oxygen supply left at that time.

It is possible that after the tourniquet is opened the cells are incapable of taking up oxygen rapidly from the inflow of arterial blood to the tissue that has been ischaemic and that a part of the oxygen-containing blood by-passes the capillaries via shunts between arterioles and venules. However, the situation becomes normal fairly rapidly, and after five minutes the  $p\text{O}_2$  values are the same in both upper limbs. It must be remembered that the blood oxygen concentration in a patient under general anaesthesia depends on the oxygen content of the gas mixture used. The  $p\text{O}_2$  values for patients under plexus anaesthesia are therefore given separately. These patients breathed only air.

The potassium value rose to 6.1 mEq./l after two hours of ischaemia and appeared to persist at that level even with continued ischaemia. The potassium value became normal rapidly after removal of the tourniquet, *i.e.* within four minutes. Only a small quantity of potassium seems to escape from the tissues in these operations and during ischaemia. The intracellular potassium value is normally about 30 times the extracellular value. The balance depends on the energy supply. When the supply of energy is inhibited, some potassium obviously

escapes from the cells. A surgical injury can also contribute to the elevation of the potassium content. This makes it all the more obvious that our measures did not greatly upset the energy balance of the tissues.

The pyruvate values continued to rise after the opening of the tourniquet. The explanation may be that glycolysis produced pyruvate from glycogen and that it is not disintegrated immediately by catabolism. However, the amount of glycogen-produced energy is probably small since the elevated  $p\text{CO}_2$  inhibits the anaerobic decomposition of glycogen to lactate. The lactate concentration remained elevated for some 30 min. after the removal of the tourniquet, but the values were not high. The lactate concentration rises steeply as a function of the duration of ischaemia.

The concentration of lactate and pyruvate are not directly correlated with the BE changes. The reason for this phenomenon is discussed elsewhere (*Närvänen 1966*).

The observation period appeared to be too short for CPK determinations.

#### CONCLUSIONS

Although a metabolic balance prevails between tissues and blood, its dynamic character does not warrant far-reaching conclusions.

Ischaemia-induced acidosis is not particularly severe. It displays features of both metabolic and respiratory acidosis. The acidosis is neutralised rapidly as the circulation returns to normal.

Anoxia during ischaemia is corrected rapidly. It seems that there is no large demand on the oxygen reserves of the myoglobin in the muscular tissue.

In view of the paucity and the deviation of the findings, it would be venturesome to draw conclusions on the basis of the lactate-pyruvate ratio. The rather slight increase in the potassium value shows that both the ischaemia and the operation caused only a slight tissue trauma from the energy standpoint.

Transfer of energy between muscle cell and nerve cell is difficult to discuss on the strength of these results.

As the limb to be operated on is hypothermal because of ischaemia (*Déry et al.*), the metabolic processes slow down. When our results are compared with known characteristics of muscle metabolism, it may perhaps be said that muscular tissue at any rate has sufficient energy

reserves to maintain post-ischaemic recuperation processes when the ischaemia is as long as it was here.

That acidotic blood with a high  $\text{CO}_2$  content rushes into the systemic circulation at the moment ischaemia is discontinued may be of clinical significance. The elevated  $\text{pCO}_2$  may aggravate the fall in blood pressure which is always demonstrable when the tourniquet is removed and the vessels of the exsanguinated limb fill with blood. The high  $\text{CO}_2$  concentration probably causes vasodilatation and exacerbates the irritability of the myocardium. If the myocardium is sensitised to arrhythmia in advance, *e.g.* by adrenalin or halothane, such an increase in acidosis may lead to a functional cardiac disorder. This is particularly true of patients who have previously been acidotic, have poor pulmonary function and a previously elevated  $\text{CO}_2$  value. However, the acidosis after the ischaemic phases described here is so mild and of such short duration that it can hardly harm a patient in good condition.

#### SUMMARY

The metabolic changes caused by tourniquet ischaemia were studied in 20 patients subjected to reconstructive operation on the upper limb. All the determinations were made in venous blood. Moderate acidosis was established in the ischaemic limb. The condition was metabolic acidosis in which the carbon dioxide content was elevated. The acidosis increased as a function of the duration of ischaemia, but disappeared rapidly when the circulation was normalised. The blood potassium rose to an average of 6.1 mEq/l. The lactate and pyruvate content increased as a function of the duration of ischaemia, but neither reached high levels. Both the ischaemia and the surgical intervention seem to have caused only a slight and rapidly corrected tissue injury as far as energy balance is concerned.

#### RESUME

Les modifications métaboliques causées par ischémie au tourniquet ont été étudiées pour 20 malades chez lesquels il a été procédé à une opération reconstructive du membre supérieur. Toutes les déterminations ont été faites à partir du sang veineux. Une acidose modérée a été constatée dans le membre ischémique. Il s'agissait d'une acidose métabolique dans laquelle la teneur en barbone dixide était plus élevée. L'acidose s'est accrue en fonction de la durée de l'ischémie, mais disparut rapidement dès que la circulation fut à nouveau normalisée. Le potassium du

sang s'est élevé à une moyenne de 6.1 mEq/l. La teneur en lactate et pyrovalate s'est accrue en fonction de la durée de l'ischémie, mais n'a jamais atteint un niveau très élevé. Tant l'ischémie que l'intervention chirurgicale ne semblent avoir causé qu'une faible lésion tissulaire, rapidement corrigée en ce qui concerne l'équilibre de l'énergie.

#### ZUSAMMENFASSUNG

Die metabolischen Veränderung, die durch Blutleere bei 20 Patienten entstanden, an denen eine Wiederherstellungsoperation der oberen Gliedmasse ausgeführt worden war, wurden untersucht. Alle Bestimmungen wurden an venösem Blut gemacht. Moderate Acidose wurde an der ischämischen Gliedmasse festgestellt. Der Zustand war eine metabolische Acidose, in der der Carbondioxidinhalt erhöht war. Die Acidose nahm als eine Funktion der Dauer der Blutleere zu, verschwand aber rasch wenn die Zirkulation wiederum normal wurde. Der Blutkaliuminhalt stieg zu einem Durchschnitt von 6.1 mEq/l. Der Laktat und Pyruvatinhalt stieg als eine Funktion der Dauer der Ischämie, aber keiner von beiden erreichte hohe Werte. Sowohl die Blutleere als auch der chirurgische Eingriff scheinen nur einen leichten und rasch korrigierten Gewebsschaden hinsichtlich des Energiegleichgewichtes hervorgerufen zu haben.

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