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Hypothermic protection (26–25°C) without perfusion cooling for surgery of congenital cardiac defects using prolonged occlusion

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ABSTRACT Open heart surgery was performed without perfusion under deep hypothermia in 343 patients with congenital heart defects aged from 1 year 3 months to 44 years. Cooling to a temperature of 26–25°C in the oesophagus was achieved by covering the body with crushed ice. The patients were maintained under superficial ether narcosis and they were given morphine (0·5 mg/kg) and tubocurarine (0·5–1·0 mg/kg). The duration of circulatory arrest was 30 minutes in 190 and longer in 153 patients—60–77 minutes in 10 patients. It took an average of 7·6 minutes for resumption of normal cardiac activity after circulatory arrest prolonged beyond 60 minutes. Of the 343 patients operated on 32 (9·3%) died. Analysis of the mortality pattern showed that patients with acute cardiac insufficiency contributed most to the total number of deaths (19 patients, 5·5%); those with pulmonary oedema ranked second (4 patients, 1·2%) and those with brain oedema third (3 patients, 0·9%). Neurological complications were observed in 13 patients (3·8%). Their frequency was significantly related to the duration of circulatory arrest. Circulatory inadequacy in patients with poor myocardial function who had undergone extensive repair appeared to be a contributory factor. The results obtained without perfusion under deep (26–25°C) hypothermic protection suggest that 75 minutes is a safe time, in terms of brain damage, for circulatory arrest. Under these conditions complex cardiac defects can be repaired.

Introduction

Hypothermia as a method providing conditions for performing open heart surgery has been used for more than 30 years. This method has drawbacks, however, one of the major ones being the limited time that circulatory arrest can be tolerated. Because of these drawbacks, and the success of extracorporeal circulation, hypothermia using surface cooling has been superseded. The method of deep hypothermia using surface cooling, introduced by Horiuchi *et al* in 1963,[1] was not used widely because of the possible haemodynamic complications developing during cooling and the post-occlusion period of rewarming. A simple, reliable method of hypothermic protection taking account of all these considerations was therefore developed at the Institute of Circulation Pathology, Novosibirsk.[2] This method was the result of a decade of preliminary research (1960–70). The improved method allowed us, under conditions of hypothermia of 30–28°C to prolong the time of safe circulatory arrest to 35–40 minutes. More than 6000 open heart operations have been performed.[3–6] Correction of the more complex defects was, however, associated with certain difficulties because hypothermia at this level did not afford sufficient time for intervention. This prompted us to search for more effective ways and means of hypothermic protection. Our observations indicated that the method of deeper hypothermia (26–25°C) provides the conditions we sought. To our knowledge, there are no published reports on the application of deeper hypothermia for circulatory arrest. This encouraged us to share our experience of the surgical treatment of congenital cardiac defects under conditions of perfusionless hypothermia (26–25°C) with prolonged occlusion (up to 60–70 minutes).

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Methods

From January 1984 to November 1985 open heart surgery was performed in 343 patients. Their ages

ranged from 1 year 3 months to 45 years (age and diagnoses shown in tables 1 and 2). Eighty of the 343 patients were categorised as poor operative risks; 47 had been operated on previously, and seven patients had a pulmonary pressure equal to the aortic pressure, a left to right shunt, and a ventricular septal defect. In 26 patients there were severe myocardial changes as a result of longstanding progression of the disease.

Ether anaesthesia with morphine (0·5 mg/kg) was administered. The depth of anaesthesia was maintained at level III_1 (Guedel). Tubocurarine (1 mg/kg) was used for muscular relaxation; the total dose of tubocurarine was reduced to 0·5 mg/kg for cyanotic patients who were in a poor condition. Infusion treatment during cooling included the administration of a solution of low molecular weight dextran (10 ml/kg). The patients received heparin (0·6 mg/10 kg) or insulin (0·5 U/kg) just before the cooling procedure was started.

Cooling was achieved by covering the patient's body with crushed ice. The temperature was measured in the oesophagus. As soon as a temperature of 32–30°C was reached in the oesophagus (35–34°C in infants) the ice was removed, and thoracotomy was performed at a temperature of 29–28°C. The cooling rate was maintained at 1°C/4–6 min in children with body weights less than 20 kg and 1°C/7–9 min in patients with body weights exceeding 40 kg. Subsequent decrease in body temperature (partial cooling) was produced by placing ice bags ("cloth helmets") on the head and plastic bags of ice under the lower back and abdomen.

When an oesophageal temperature of 26–25°C was reached, we proceeded to prepare for the intracardiac stage of the operation. The oesophageal temperature at the time of maximum cooling before circulatory arrest in patients with various defects are given in table 5. Ventricular fibrillation developed at 25°C in two patients; this complication persisted despite defibrillation. The great vessels were promptly occluded and the major steps of the surgical intervention carried out.

To ensure reserve alkalosis during cardiac arrest a 4% solution of sodium bicarbonate was administered (2 ml/kg). Heparin (2 mg/kg) was repeatedly administered into the heart before the circulation was arrested. Before occlusion of the great vessels (the aorta, pulmonary artery, upper and lower vena cavae), a cold cardioplegic solution (0–4°C) was injected into the occluded aorta. Its composition was as follows: 5% glucose solution; 3·0–3·5 mmol/l potassium chloride; 2·0 mmol/l sodium bicarbonate; 2·0 mmol/l magnesium sulphate; 75 mg/l prednisolone; 60 mg/l heparin (pH 7·8–7·9; 300 mEq (mosm)/l). The cardioplegic solution was injected in a volume of 5–8 ml/kg. After cardioplegic arrest the temperature of the myocardium was in the range 15–20°C. Repeated cardiac arrest was achieved by prolonging occlusion to 40 minutes. The distribution of occlusion times is shown in table 3. The longest that had a good outcome was 77 minutes. To prevent venous hypertension of the brain during circulatory arrest, blood was vented through a catheter inserted into the superior vena cava. The amount of blood thus vented was 5–10 ml/kg every 10 minutes of occlusion. The pressure in the superior vena cava was maintained at 4–6 mm Hg. The evacuated blood was returned to the patient when the occluding clamps were removed. After occlusion was discontinued and circulation restored, effective cardiac function was achieved by manual cardiac massage and administration of cardiotonic drugs. The duration of rewarming was related to body weight. The mean time was 85 (SEM 2) minutes for children with body weights less than 20 kg, 94 (4) minutes for those weighing 20–40 kg, and 103 (5) minutes for those weighing more than 40 kg.

Table 1 *Distribution of patients by age group*

Age (y)	*No of patients*
<3	34
3–7	143
8–14	119
15–25	35
26–45	12
Total	343

Table 2 *Distribution of patients by diagnosis*

Diagnosis	*No of patients*
Atrial septal defect—secundum	47
Pulmonary stenosis	9
Ventricular septal defect	110
Atrial septal defect—primum	24
Aortic stenosis	16
Fallot's triad	16
Fallot's tetralogy	78
Valvular insufficiency	18
Ventricular septal defect—aortic insufficiency	6
Double outlet right ventricle	6
Transposition of great arteries	1
Other defects	12
Total	343

Table 3 *Duration of circulatory arrest in operated patients*

Occlusion duration (min)	*No of patients*
<30	190
30–39	76
40–49	43
50–59	24
60–75	10
Total	343

Table 4 *Time needed to restore adequate circulation in relation to duration of circulatory arrest*

Occlusion duration (min)	Mean (SEM)		
	Oesophageal temperature with maximum cooling (°C)	Occlusion duration (min)	Time to restoration of adequate circulation (min)
<10	27·1 (0·1)	7·6 (0·5)	1·7 (0·3)
10–19	26·8 (0·2)	15·3 (0·5)	4·1 (0·3)
20–29	26·2 (0·3)	24·5 (0·3)	4·2 (0·2)
30–39	26·0 (0·4)	34·6 (0·3)	5·3 (0·3)
40–49	25·4 (0·2)	44·2 (0·4)	5·8 (0·5)
50–59	25·7 (0·3)	53·0 (0·7)	7·6 (1·1)
>60	24·9 (0·3)	67·0 (1·8)	7·6 (1·1)

The surgical approach was by bilateral transpleural transverse sternotomy.

The time needed to restore adequate cardiac action related to the duration of occlusion is shown in table 4. After return to the intensive care unit the average duration of ventilatory assistance was three to six hours in the case of simple lesions and short term occlusion; when the defects were complex and occlusion was prolonged patients were extubated during the night. The patients were awake by the time rewarming was terminated, two to four hours after the surgical procedure irrespective of the duration of the occlusion.

Results

The results of the surgical treatment are summarised in table 5. The best results were obtained in the group with simple defects (atrial septal defect, type II, secundum; pulmonary valve stenosis). There were no deaths in this group of 56 patients. A ventricular septal defect was repaired in 110 patients, three of whom died; of these three, two were small children (aged 1 year 3 months and 2 years) who had profound changes of the myocardium and severe pulmonary hypertension. The third patient died from irreversible neurological complications caused by drastic haemodynamic shifts before cooling was started; this very hypertensive patient also had a long history of the disease.

Twenty four patients were operated on for a septum primum atrial septal defect, and three of these had an associated ventricular septal defect. The time needed for the accomplishment of the intracardiac stage of the operation was 26–59 minutes at a mean oesophageal temperature of 25·9° (SEM 0·2°) C. There were three deaths in this group: one patient died from cardiac arrhythmia unresponsive to treatment, another died of haemorrhage through a fragile wall of the aorta, and the third died from acute insufficiency of an underdeveloped left ventricle.

Sixteen patients were operated on for aortic stenosis. Here the surgical results were related to the severity of the myocardial lesion at the time of the operation. After valvulotomy a cusp of the aortic valve prolapsed in eight of 16 patients. To prevent the development of aortic insufficiency the aortic cusps were repaired by atraumatic sutures with the use of synthetic pads. There were no deaths among the 11 patients classified as grade III according to the criteria of the New York Heart Association. Of the five patients classified as grade IV on these criteria, two died after aortic valvulotomy with use of synthetic sutures. The pertinent findings in the patients were pronounced concentric hypertrophy of the myocardium, a small chamber of the left ventricle, and gross deformity of the leaflets of the aortic valve with the valve annulus narrowed by calcinosis.

Sixteen patients were operated on for the triad of Fallot. There was one death in this group, in a case of far advanced disease, a high pressure gradient at the level of the pulmonary artery, and a very small chamber of the right ventricle. This patient died because the hypertrophied right chambers of the heart made proper surgical relief of the defect impossible.

Most difficulties were encountered in the correction of Fallot's tetralogy. This group consisted of 78 patients. Correction of the lesion included insertion of a patch close to the defect, relief of pulmonary valve stenosis, resection of the infundibulum, and repair of the outflow tract of the right ventricle by means of pericardial tissue when necessary. Among these 78 patients who had a radical operation, previously constructed pulmonary to systemic anastomoses were concomitantly closed in 20; patients in this group were categorised as poor operative risks. The surgical intervention was palliative in five patients. Of the patients with Fallot's tetralogy, the condition was mild in 25, moderately severe in 15, and severe in 38. The duration of occlusion was 33–77 minutes at a mean temperature of 25·8° (SEM 0·3°) C. Of 78 patients operated on, 15 died at different times after the surgical intervention. The most frequent causes of death were acute cardiac insufficiency (nine patients) and pulmonary oedema (four patients). There was one death from cerebral oedema and another one from massive pulmonary haemorrhage, and in the latter patient there was an indication in his case history that he had had pulmonary tuberculosis. Five of the 20 patients with the severe form of Fallot's tetralogy with previously constructed anastomoses died in this group.

Eighteen patients were operated on for valvular insufficiency—aortic in eight, mitral in five, tricuspidal in one; Ebstein's anomaly was present in four. Circulatory arrest lasted for 40–75 minutes at a mean temperature of 25·8° (SEM 0·2°) C. Cardiac action was

Table 5 *Results of operative treatment of patients with congenital cardiac defects*

Diagnosis	*Mean (SEM)*			*No of patients*	*No (%) of deaths*
	Oesophageal temperature, with maximum cooling (°C)	*Occlusion duration (min)*	*Time to restoration of adequate circulation (min)*		
Atrial septal defect—secundum	27·0 (0·1)	9·7 (0·7)	2·1 (0·4)	47	—
Pulmonary stenosis	26·9 (0·2)	9·0 (2·2)	1·5 (0·6)	9	—
Ventricular septal defect	25·8 (0·3)	28·7 (1·0)	4·3 (0·2)	110	3 (2·7)
Atrial septal defect—primum	25·9 (0·2)	40·0 (2·2)	4·4 (0·3)	24	3 (12·5)
Aortic stenosis	26·7 (0·3)	23·6 (2·0)	6·6 (0·8)	16	2 (12·5)
Fallot's triad	27·2 (0·1)	10·1 (1·5)	3·1 (0·7)	16	1 (6·2)
Fallot's tetralogy	25·8 (0·2)	38·3 (1·4)	5·5 (0·3)	78	15 (19·4)
Ventricular septal defect with aortic insufficiency	25·8 (0·2)	49·7 (4·0)	7·7 (1·3)	6	2 (33·3)
Valvular insufficiency	25·8 (0·2)	53·6 (2·1)	7·0 (0·7)	18	2 (11·1)
Double outlet right ventricle	24·8 (0·6)	50·5 (1·5)	5·2 (0·6)	6	1 (16·7)
Transposition of great arteries	24·8	61·0	13·0	1	—
Other defects	26·8 (0·4)	17·4 (2·9)	3·2 (0·9)	12	3 (25·0)
Total				343	32 (9·3)

restored in an average of 7·0 (SEM 0·7) minutes. There were two deaths: one patient with Ebstein's anomaly died from acute cardiac insufficiency due to the very small size of the left heart, and the second had cardiac insufficiency leading to weak heart activity and ultimately death. There were six patients in the group with a ventricular septal defect associated with aortic insufficiency. In all of these patients the ventricular septal defect was repaired, as was the aortic valve annulus; the aortic valve was replaced by a prosthesis in one patient. In this group two patients died from acute cardiac insufficiency due to the pre-existing changes in the myocardium; the coronary circulation was abnormal (no left coronary artery) in the other patient.

The group with complex defects included a double outlet right ventricle (six patients) and transposition of the great arteries (one patient). In this group, one patient with a double outlet right ventricle died after the correction; the cause was poor function of the left ventricle. One patient aged 7 years with transposition of the great arteries had the Mustard-Brom procedure. The functional results were good when reviewed 18 months after surgery.

Table 6 *Causes of death among the 343 patients*

Cause	*No (%) of patients*
Acute cardiac insufficiency	19 (5·5)
Pulmonary oedema	4 (1·2)
Haemorrhage	3 (0·9)
Cerebral oedema	3 (0·9)
Sepsis	2 (0·6)
Acute renal insufficiency	1 (0·3)
Total	32 (9·3)

The last group was composed of 12 patients with rare defects. Three patients died in this group. They all died because of inadequate correction of anatomically complex lesions (there was an associated primum atrial septal defect with a complex lesion of the mitral valve in two patients, and severe infundibular stenosis of the outflow tract of the right ventricle with almost no cavity in one patient).

The mortality rate was greatest in the group of patients with a high operative risk. In this group 21 of the 80 patients died (26%).

A survey of the mortality pattern shows that primary acute cardiac insufficiency was the major cause of death (table 6). The symptoms and signs of acute cardiac insufficiency were treated with dopamine. Eighty of 343 patients (23·3%) were found to have acute cardiac insufficiency at the time of operation. Acute cardiac insufficiency was relieved within one day of operation in 45 cases and within two days in 16 cases; it progressed, resulting in death, in 19 cases. In the group of 19 patients with sharply progressing cardiac insufficiency were six cases of unrestored cardiac action after completion of the major steps of the operation and discontinuation of occlusion. In these cases pre-existing myocardial changes, particularly when associated with abnormal coronary circulation, were considered responsible for the failure to restore cardiac action.

Neurological complications were observed in 13 of the 343 treated patients (3·8%, table 7). There were symptoms of local brain damage as a result of air embolism in five patients. The neurological symptoms were indicative of general brain damage in eight patients; brain oedema was the cause of death in three patients in this group. As table 7 shows, the frequency of neurological malfunction increased with the dura-

Table 7 *Frequency of neurological complications in relation to duration of circulatory arrest*

Occlusion duration (min)	*No of patients*	*No of neurological complications*	*Outcome*		
			Complete reversibility	*Residual manifestations*	*Death*
<30	190	2	2	—	—
30–39	76	1	—	—	1
40–49	43	5	4	1	—
50–59	24	4	—	2	2
>60	10	1	1	—	—
Total No (%)	343	13 (3·8)	7 (2)	3 (0·9)	3 (0·9)

tion of circulatory arrest. When the great vessels were occluded for 40–49 minutes the increase was significant ($p < 0·01$) and when occluded for 50–59 minutes the increase was highly significant ($p < 0·001$, χ^2 test). Circulation was arrested for more than 40 minutes in the patients with associated cardiac defects. In 26 of these (34%) the state of the myocardium was poor. These patients were subjected to multiple reconstructive operations with a view to restoring the state or function of the valve and septa. Thus haemodynamic inadequacy was the cause of neurological impairment in six patients; two of these suffered a deterioration in their haemodynamic state before the major step of the operation was performed, and four during the post-occlusion period. In the remaining two of the eight patients the neurological sequelae were due to inadequate hypothermic protection.

The neurological function reverted to normal in seven of the 13 patients discharged from hospital. In three patients there were signs of residual malfunction, which disappeared in one.

Discussion

Open heart surgery performed under hypothermic cardiac arrest inevitably raises the question of the state of the central nervous system. The frequency of neurological complications attendant on deep hypothermia ranges from 1% to 3%.[7] Neurological complications were observed in 3·8% of the patients we operated on, and the frequency was related to the duration of arrest.

The results show that the neurological complication rate increases significantly with the duration of occlusion. This raises the question of the extent to which poor haemodynamics is responsible for the increase in neurological complication rate. We found that the frequency of neurological malfunction was indeed associated with unstable haemodynamics after prolonged occlusion. We observed that circulatory arrest was directly responsible for brain damage in 0·6% of the patients when the method of perfusionless deep hypothermia was first applied. This was accounted for by the lack of prophylactic measures against venous hypertension of the brain.

Where the depth of cooling is adequate and duration of occlusion is not extended, neurological complications are not as a rule expected. The safe duration for circulatory arrest is generally accepted to be 30 minutes at 25°C, and 60 minutes at 20°C.[7,8] The advantage of perfusionless deep (26–25°C) hypothermia, however, is the possibility of safely arresting the brain circulation for as long as 75 minutes at 25°C. This safety is provided by strict adherence to the principles of anaesthesiological and pharmacological support of hypothermia. The principles include (1) superficial ether anaesthesia under conditions of severe respiratory alkalosis combined with rapid active cooling; (2) maintenance of an adequate haemodynamic state at all stages of hypothermia; (3) additional cooling of the head to achieve a temperature of the brain lower than that of the other internal organs; (4) prevention of venous hypertension of the brain during occlusion; (5) forced diuresis after occlusion (10–20 ml/kg an hour); (6) rapid rewarming to a body temperature of 34–36°C.

The effects of hypothermic occlusion on the central nervous system have been studied by neuropsychological methods.[9] The results showed that perfusionless hypothermia (26–25°C), in the case of a course without neurological sequelae, entails no brain malfunction. Normal brain activity is retained irrespective of the duration of the circulatory occlusion. One of our patients was under observation for 2½ years after operation with circulatory occlusion extended to 77 minutes at 25°C. The long term findings on brain function after perfusionless hypothermia are in preparation.

Our surgical experience shows that hypothermic protection (26–25°C) is a simple and reliable method

providing conditions for open heart surgery in all age groups. The merits of the method are ease of performance and substantial decrease in the number of postoperative pulmonary complications and haemorrhages due to interference with haemostasis. With this method of hypothermic protection the probability of acute haemodynamic deterioration at various steps of the operation is reduced. This allowed us to use the technique for radical surgical correction in a group of patients with a poor state of the myocardium and at high operative risk.

The surgical results for aortic stenosis and valvular insufficiency of class IV when the disease is far advanced suggest to us that perfusionless hypothermia is being applied later than appropriate. The complications and mortality resulting from surgical treatment under conditions of deeper hypothermia can be reduced to low levels provided that the patients are strictly selected.

The method developed may be helpful in solving the problem of brain protection against the effect of hypoxia. From the observations made it is reasonable to conclude that 75 minutes is a safe limit for circulatory arrest at 25°C. This time limit gives ample opportunities for the performance of virtually all types of surgical interventions in patients with congenital cardiac defects.

Thus the method of deeper perfusionless hypothermic protection (26–25°C) is effective in providing good conditions for operations on the open heart. It can be used successfully in cardiac surgery.

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