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Cellular aggregation and trauma in cardiotomy suction systems

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ABSTRACT Experiments in dogs showed that the high levels of cellular aggregation and trauma caused by cardiotomy suction can be considerably reduced by the avoidance of air aspiration. A hypothesis is proposed to explain this on the basis of shear stresses in the inlet cannula. Roller pump suction was also found to be slightly more traumatic than vacuum suction, but contact of the blood with the pericardium had no effect so long as the pericardium and epicardium had been previously washed with saline.

Examination of the factors responsible for cellular aggregation and trauma during extracorporeal circulation for open heart surgery showed that these effects could be largely avoided by simple technical precautions, but that further studies of the cardiotomy suction system were required (Wright, 1976, 1977). Other investigators have reported that cardiotomy suction is responsible for severe haemolysis (Morris *et al*, 1965; Wells *et al*, 1968), particulate embolisation (Page *et al*, 1974; Solis *et al*, 1974, 1975), the formation of fat globules (Caguin and Carter, 1963; Wright *et al*, 1963; Evans and Wellington, 1964), and the generation of gas microbubbles (Loop *et al*, 1976; Furness, 1977). Microemboli pumped into the patients' systemic arteries are thought to cause embolic tissue damage, but this can be reduced by microfiltration of the cardiotomy suction blood (Hill *et al*, 1970; Osborn *et al*, 1970; Katsumoto *et al*, 1973; Skagseth *et al*, 1974).

There are several possible explanations for the cell trauma in the cardiotomy suction system. Morris *et al* (1965) claimed that the high levels of plasma haemoglobin in cardiotomy suction blood were due to contact of the blood with the pericardium. Rygg (1973), however, found that the haemolysis could be reduced by the reduction of air aspiration and by the use of a low pressure suction system (vacuum) instead of a roller pump. Possibly the low pressures generated in the suction system could be responsible for the haemolysis, but this seems unlikely since Wielogorski *et al* (1975) showed that haemolysis was only minimal so long as the absolute pressure exceeded 150 mmHg.

Thus the hypotheses to be tested are that cardiotomy suction causes cellular aggregation and trauma; that the aggregates can be removed by filtration; that this will reduce tissue damage; that contact of the blood with the pericardium causes haemolysis; that vacuum suction causes less haemolysis than roller pump suction; and that the haemolysis can be reduced by the avoidance of air aspiration.

Materials and methods

For in-vivo experiments 36 beagle dogs 10·4–27·6 kg (mean 13·4) body weight were anaesthetised by an intravenous injection of 0·4–0·5 g thiopentone sodium (Intraval), intubated, and provided with intermittent positive-pressure ventilation by an East Radcliffe ventilator delivering equal flow rates of oxygen and nitrous oxide in a semi-closed circuit. Anaesthesia was maintained for about five hours by the continuous intravenous infusion at 1 ml/min of 0·9% sodium chloride containing 0·4 g Intraval per 100 ml.

A mid-line thoracotomy was performed, and the pericardium was incised so that the cut edges could be sutured to the thoracic rim to form a pericardial well. Sodium heparin, 300 IU/kg body weight was given via a femoral vein, and a 6 mm or 9 mm internal diameter Polystan polyvinyl chloride catheter was inserted into the left atrium via the atrial appendage.

The extracorporeal circuit is shown diagrammatically in figs 1a and b. The circuit consisted of a Travenol SM0305 rigid cardiotomy reservoir, a Bio-Med Engineering torpedo type stainless steel heat exchanger, and a Travenol 6LF pump set. Roller pump suction was provided by a Sarns roller pump, and vacuum suction was obtained by an Associated Electrical Industries exhauster/compressor coupled

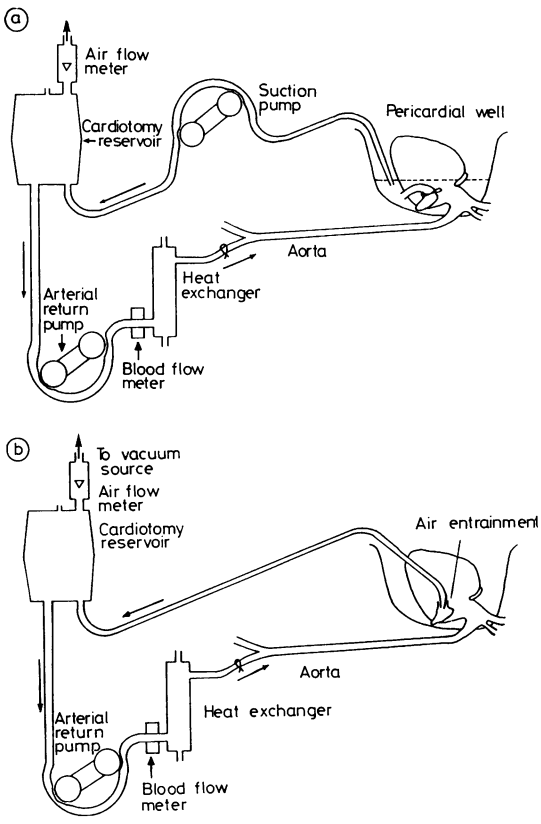

Fig 1 (*a*) *Experimental circuit showing direct collection of blood from left atrium using vacuum suction system.* (*b*) *Experimental circuit showing aspiration of a blood/air mixture from pericardial well using roller pump system.*

to the cardiotomy reservoir. Tubing lengths were standard for all experiments so that the 4 mm internal diameter stainless steel cannula (within the left atrial catheter or in the pericardial well) was connected to the cardiotomy reservoir by 1 m of 6 mm internal diameter polyvinyl chloride tubing. The circuit was primed with 500 ml Ringer-lactate solution, 5 ml 8·4% sodium bicarbonate, and 100 IU/kg body weight sodium heparin.

The left atrial catheter was bisected at the level of the left atrium so that blood could be removed either directly from the left atrium (seven experiments with roller pump and five with vacuum suction) or after it had pooled in the pericardial well (eight experiments with roller pump and 10 with vacuum suction). The suction source was regulated so that all of the blood leaving the left atrial catheter was removed and an equal flow rate of air was also drawn into the system. During both roller pump and vacuum suction the pressure in the suction tube close to the cannula varied from −4 mmHg at a blood flow rate of 200 ml/min to −10 mmHg at 1000 ml/min. After passing through the cardiotomy reservoir, the blood was returned at 37·0±1·0°C to the animal via the left common femoral artery by another Sarns roller pump. Thus the vacuum suction circuit contained one roller pump and the roller pump suction circuit contained two roller pumps. Blood flow rate was measured by means of a Nycotron extracorporeal flow transducer in the arterial line and a Nycotron type 376 blood flowmeter. The flow rate of air was measured at the cardiotomy reservoir vent by a calibrated bobbin flowmeter.

Blood and air suction from the left atrium or pericardium and blood reinfusion into the femoral artery were continued for one hour except in the control group, when they were limited to five minutes to mix the blood and circuit prime in the same proportions as in the experimental group. After one hour the blood remaining in the cardiotomy reservoir was infused into the femoral artery, and the animals were observed under anaesthesia for a further hour.

Throughout the suction and recovery periods measurements were made of the suction line, cardiotomy reservoir, reinfusion line, and arterial and venous blood pressures using Bell and Howell strain gauge pressure transducers and Devices amplifiers; and of heart rate, oesophageal and blood temperatures, and blood and air flow rates at 15-minute intervals with one additional measurement five minutes after starting suction.

Blood samples were taken from the left atrium and femoral artery for measurements of platelet and leucocyte aggregation by the screen filtration pressure (SFP) technique of Swank *et al* (1964); platelet and leucocyte counts by phase contrast microscopy; and packed cell volume, red cell osmotic fragility, whole blood haemoglobin concentration as cyanmethaemoglobin, and plasma haemoglobin concentration by the benzidine technique (Crosby and Furth, 1956). Blood smears were stained with Leishman and Giemsa stains.

Data relating to plasma haemoglobin concentration and to platelet and leucocyte counts were adjusted to correct for haemodilution, so that all values are referred to a standard packed cell volume of 0·40. The traumatic index was calculated as the change in plasma haemoglobin concentration after 100 passages of the calculated whole blood volume through the circuit (Koller and Hawrylenko, 1967).

The SFP measurements were corrected for changes in haemodilution by constructing correction graphs based upon serial dilutions of ten blood samples with initial SFP values in the range 28–525 mmHg and measuring the SFP at seven different dilutions of each blood sample. The curves were

found to be linear biphasic with a minimum turning point at PCV $\simeq$ 0·17. The slope (a) of the phase above PCV $\simeq$ 0·17 was linearly related to the initial values of SFP and PCV. Thus:

$$a \propto \frac{SFPi}{PCVi}, \text{ and}$$

$$\frac{1{\cdot}4925\ SFPi}{PCVi} = \frac{dSFP}{dPCV}$$

Using this result, the appropriate correction curve was selected according to the value of $\frac{SFPi}{PCVi}$ taken from the measurements on the blood sample immediately after the induction of anaesthesia. All SFP measurements were then adjusted to give the SFP corresponding to PCV=0·40. This is referred to as $SFP_{0{\cdot}40}$. There was no constant relationship between the SFP measurements on serially diluted blood samples and the screen filtration resistance (SFR) value used for a similar purpose by Page *et al* (1974).

During five preliminary experiments it was found important to wash the pericardial well with 40 ml saline before admitting any blood to the suction system. Failure to do so resulted in immediate massive platelet aggregation, the SFP exceeding the maximum value measurable of 600 mmHg after only five minutes of suction. These experiments were excluded from the series.

The 20 animals that survived until the end of the recovery period were exsanguinated via the right atrium. Tissue samples were taken from the brain, heart, lung, liver, kidney, spleen, and jejunum and immersion-fixed in 2% phosphate buffered formaldehyde for histology. Sections were stained with haematoxylin and eosin, and with a modified picro-Mallory stain for platelets (Carstairs, 1965).

Because of the probability that the inclusion of an animal in the circuit could alter the concentrations of cellular aggregates and plasma haemoglobin, 13 additional experiments were performed in vitro. Seven were used to compare roller pump and vacuum suction systems and the other six to examine the effects of aspirating air as well as blood. For these experiments the animals were anaesthetised with Intraval and given 300 IU/kg body weight of sodium heparin before collecting 500 ml blood from a femoral artery into a sterile empty polyvinyl chloride blood pack.

Two circuits identical to the one used for the in-vivo experiments were constructed, the position of the animal being occupied by a 500 ml polyvinyl chloride reservoir. Each circuit was primed with 250 ml heparinised blood, 150 ml Ringer-lactate solution, 5 ml 8·4% sodium bicarbonate, and 100 IU/kg body weight of sodium heparin. Suction was provided as before, and the blood flow rate was maintained for one hour at 450 ml/min, which was the mean flow rate measured during the in-vivo experiments.

Data were analysed for population variance and groups were compared by Student's *t*, Mann-Whitney U, and Wilcoxon rank sum tests as appropriate.

Results

All six animals in the control group survived until killed, but ten of the 30 animals in the experimental group died before the end of the recovery period. The haematological data from these ten incomplete experiments were not included in the results. The morbid signs were reduced blood flow rate from the left atrium, gradually decreasing arterial blood pressure, and apparently reduced myocardial contractility. Extensive post-mortem and histological examinations showed no indications of the cause of death other than minimal patchy atelectasis of the lungs and a recent adherent thrombus in a small branch of the left coronary artery in one dog. Platelet and leucocyte aggregates were not found, and there were no signs of embolic tissue damage.

Haematological data were analysed by parametric and non-parametric tests. Student's *t* test for unequal samples and the Mann-Whitney U test were used for in-vivo experiments, and Student's *t* test for paired data and the Wilcoxon rank sum test for in-vitro experiments. The conventional 5% probability criterion was applied in each case.

In the in-vivo experiments the increase in plasma haemoglobin concentration was significantly greater in the suction group composed of all 20 experiments (17·4±SE 3·2 mg/dl) than in the control group (5·2±SE 2·1 mg/dl) (fig 2). The change in platelet

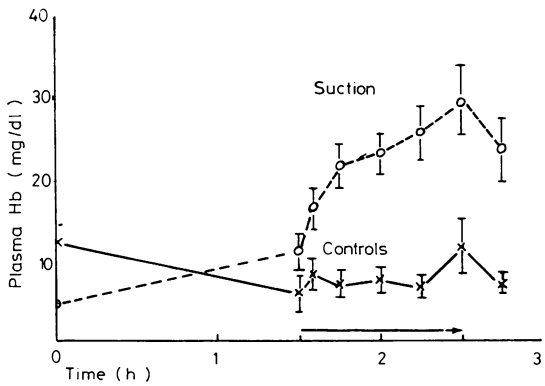

Fig 2 *Plasma haemoglobin concentration during in-vivo cardiotomy suction. Arrow indicates suction period. Vertical bars indicate one standard error on each side of mean.*

count was also significantly different in these two groups, decreasing by 23·3±SE 1·8×10⁹/l in the suction group and increasing by 61·7±SE 49·4×10⁹/l in the control group (fig 3). The haematological differences between left atrial and pericardial aspiration and between roller pump and vacuum suction were not significant.

In the in-vitro experiments, however, the increase in plasma haemoglobin concentration was significantly greater in the roller pump group (2238·1±SE 420·3 mg/dl) than in the vacuum suction group

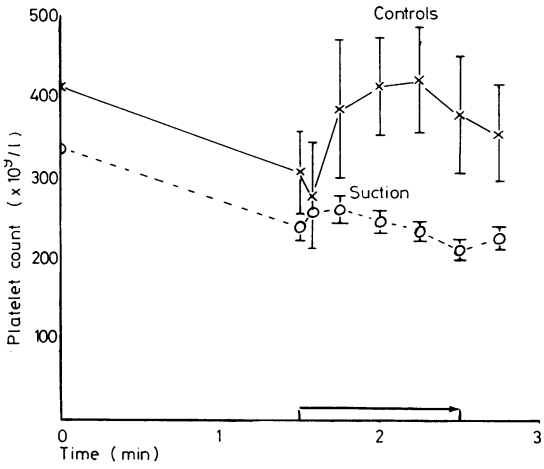

Fig 3 *Platelet counts during in-vivo cardiotomy suction. Arrow indicates suction period. Vertical bars represent one standard error on each side of mean, and arrow indicates end of the one-hour suction period.*

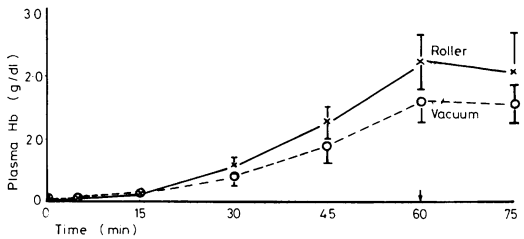

Fig 4 *Plasma haemoglobin concentration during in-vitro blood suction using vacuum and roller pumps. Vertical bars represent one standard error on each side of mean, and arrow indicates end of the one-hour suction period.*

(1591·9±SE 293·5 mg/dl) (fig 4). The most remarkable differences were found in the in-vitro experiments performed to examine the effects of air aspiration (table, figs 5–7). Each pair of values is significantly different at the 5% probability level.

Haematological changes during one-hour of suction and recirculation of dog blood. Each value shown is mean and standard error

	Fluid aspirated	
	Blood and air	*Blood alone*
Δplasma haemoglobin concentration (mg/dl)	2167·9 ±323·0	214·6 ±121·9
Δscreen filtration pressure (SFP 0·40) (mmHg)	39·2 ± 11·2	− 2·3 ± 0·8
Δpacked cell volume	− 0·12± 0·02	− 0·01± 0·0
Δplatelet count (×10⁹/l)	−264·7 ± 16·6	−100·5 ± 02·3

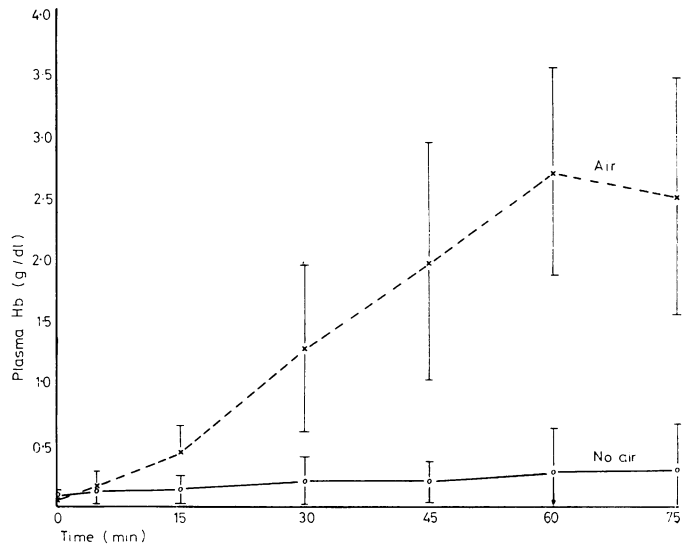

Fig 5 *Plasma haemoglobin concentration during in-vitro suction of blood and air and of blood alone. Vertical bars represent one standard error on each side of mean, and arrow indicates end of one-hour suction period.*

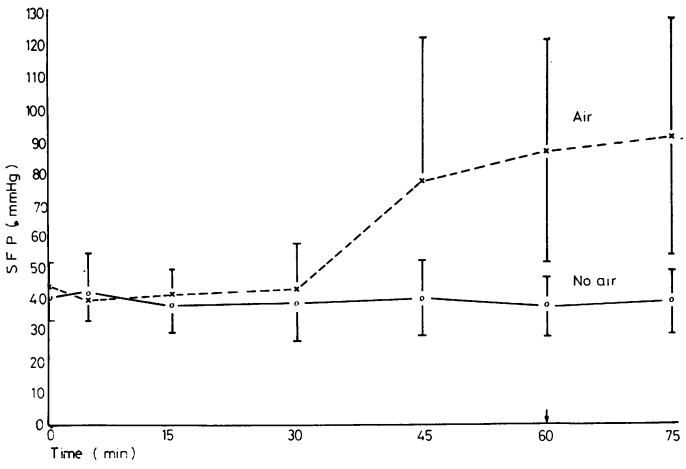

Fig 6 *Screen filtration pressure (SFP) during in-vitro suction of blood and air and of blood alone. Vertical bars represent one standard error on each side of mean, and arrow indicates end of one-hour suction period.*

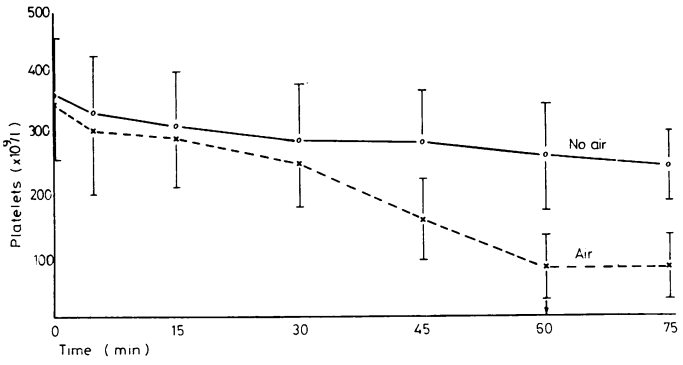

Fig 7 *Platelet counts during in-vitro suction of blood and air and of blood alone. Vertical bars represent one standard error on each side of mean, and arrow indicates end of one-hour suction period.*

Discussion

The principal conclusion to be drawn from these experiments is that cardiotomy suction of an air/blood mixture can be responsible for considerable cell destruction and platelet aggregation. This has been supported by measurements made on human blood samples taken from the oxygenator and cardiotomy reservoir during two open heart operations. The final plasma haemoglobin concentrations were 18·6 and 63·6 mg/dl in the oxygenators and 156·6 and 213·9 mg/dl in the cardiotomy reservoirs. The most likely causes of the cell changes in the suction system are the mechanical forces acting at the suction cannula. Direct observations and photography showed that blood and air flowed down the suction tube to the reservoir in short boluses with more or less parabolic velocity profiles. It was not possible to determine whether the flow was laminar within the boluses, but the fully developed flow pattern was established about 10 cm from the inlet with blood and air each being moved at 450 ml/min (total flow rate 900 ml/min). For laminar flow from a stationary reservoir, the inlet length is calculated to be 26·7 cm.

$$X = 0{\cdot}08r\,\frac{(Ud)}{V},$$

X = inlet length
r = tube radius
U = average velocity
d = tube diameter (McDonald, 1974)
V = kinematic viscosity

(The inlet length is the distance from the inlet orifice at which the flow pattern becomes fully formed.)

For laminar flow from a turbulent reservoir, the inlet length is only 1·77 cm.

$$X = 1{\cdot}386r\,\frac{(Ud)^{\frac{1}{4}}}{V}.$$

If the flow pattern through the inlet cannula was laminar and parabolic the wall shear stress would be

$$\tau_L = \mu\,\frac{dv}{dr}$$

τ_L = laminar shear stress
μ = absolute viscosity
v = velocity
r = tube radius

Figure 8 shows the relationship between blood flow rate and maximum shear stress for cannulae of 1 mm to 9 mm id up to the critical Reynold's number of 2300 ($Re=\frac{Ud}{v}$). At flow rates above the values corresponding to a transitional region of Re=2300 to 2500, the flow becomes turbulent, and the shear stresses are much higher.

Using the Poiseuille relationship, the predicted pressure drop along the cannula would be much less than 1 mmHg at 450 ml/min. The measured pressure drop was 4 mmHg. This lack of correspondence is probably because the inlet region is relatively large. The pressure drop was linearly related to blood flow rate up to 750 ml/min, at which there was a turning point and a steeper linear relation beyond. This may indicate a laminar flow up to 750 ml/min and turbulence at higher flow rates.

The relation between pressure drop and flow rate for an equal-parts mixture of blood and air was parabolic and the pressure drops were relatively higher than for blood alone (about double at a blood flow rate of 750 ml/min). This additional pressure drop does not appear to be due to the additional energy required to move the air because the viscosity

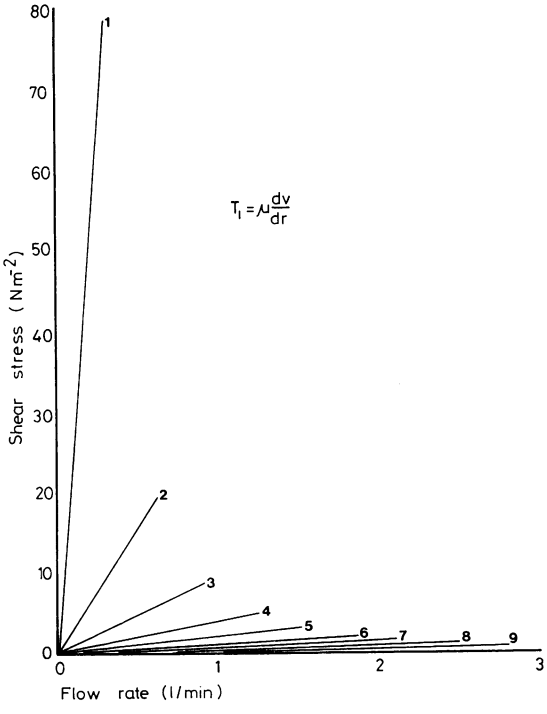

Fig 8 *Laminar shear stresses calculated for whole blood flowing through tubes 1–9 mm internal diameter. Each line terminates at critical Reynold's number (Re=2300).*

of air is so low (190·4μP at 40°C) (Weast, 1974). An alternative explanation is that the additional pressure dissipation is from local or general turbulence within the bulk flow. This would generate high local shear stresses, which could be responsible for the high rates of blood trauma during blood and air aspiration.

Schlichting (1960) has proposed the following formula to describe the stress-strain relation in fully formed turbulent flows.

$$\tau_t = e\epsilon\frac{dv}{dr} = 0{\cdot}03\,\frac{2\Delta P}{e}$$, where τt = turbulent shear stress
e = density
ϵ = eddy current kinematic viscosity
ΔP = pressure drop

Using this formula, the measured blood trauma can be explained as the result of turbulent shear stresses. Figure 9 shows the shear stress-flow rate relation for turbulent flows calculated by Schlichting's formula using the measured pressure drop along the suction cannula. The vertical broken line indicates the shear stresses corresponding to the blood flow rate used in the in-vitro experiments. The immediate cellular effects of imposed shear stresses were reported by Nevaril *et al* (1968), Goldsmith (1974), and Hung *et al* (1976). Cell trauma increases with the duration of imposition of shear stress at least for short periods (Colantuoni *et al*, 1977). Probably therefore, exposure to a shear stress of about 140N m^{-2} could cause severe cell trauma, especially when wall impact effects are included since these can be considerable (Johnston *et al*, 1975).

Thus the greatly increased levels of cell trauma during blood and air aspiration may be explained by the much higher shear stresses resulting from turbulent flow conditions. The benefits to be derived by reducing the blood flow rate, increasing the diameter of the suction cannula, and avoiding air aspiration are apparent.

The stress-strain model for turbulent flows suffers from the limitation that it is not known whether Schlichting's formula can be applied to fluid mixtures and to the two limitations mentioned above, that is, no account is taken of time-dependent and wall-impact effects. Actually these factors would be likely to increase the differences between laminar and turbulent shear effects. Furthermore, the appropriate values of e and ϵ are unknown. (In the construction of figure 9, e has been calculated as $\frac{1{\cdot}05\times1{\cdot}12+10^{-3}}{2}$.)

Finally, the exceptionally high (10^4N m^{-2}) threshold for cell deformation found by Bernstein *et al* (1977) and the exceptionally low value of 1ON m^{-2} required for platelet aggregation reported by Brown *et al* (1975) have not been included. We are left with the conclusion that the shear stress model of cardiotomy

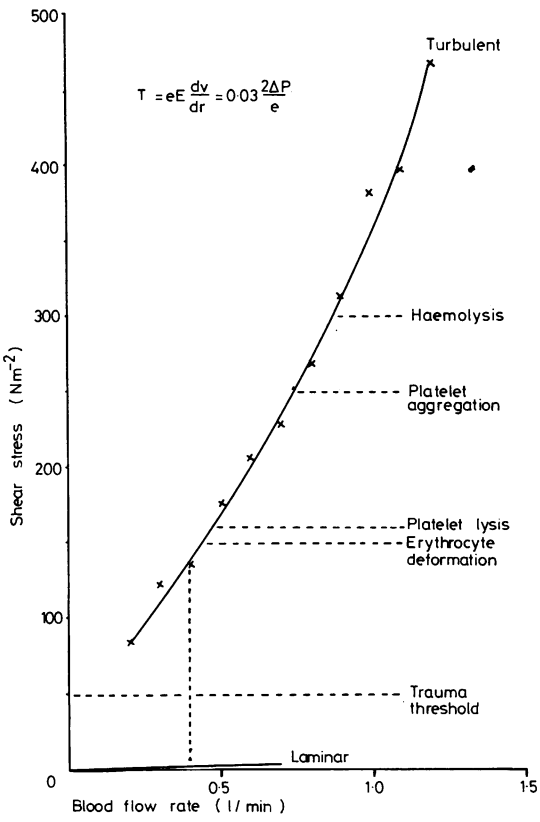

Fig 9 *Laminar and turbulent shear stresses for blood and air flowing through tubes of 4 mm internal diameter.*

suction is capable of predicting results that agree well with the measured cell trauma, but that in view of the analytical limitations and the variation in the reported data on the cellular effects of shear stress, it must be regarded as a qualitative guide. It should not be used to make quantitative predictions in its present form. Thus in a qualitative way it could be used to explain the high levels of cell trauma during blood circulation and oxygenation as due to local turbulent shear stresses in the bubble oxygenator (Wright and Sanderson, 1976).

Based on this discussion, the general conclusions are that vacuum suction will cause less cell trauma than roller pump suction, and that cell trauma can be dramatically reduced by the avoidance of air aspiration. The problem of air aspiration may be overcome by the use of a controlled suction system such as those developed by Barthelemy *et al* (1978) and by ten Duis *et al* (1978).

In conclusion, we should mention that we did not encounter the massive haemolysis of blood caused by contact with the pericardium reported by Morris *et al* (1965) and by Wells *et al* (1968). We did, however, measure severe immediate platelet aggregation during five preliminary experiments. This was avoided in the subsequent experiments by washing the pericardium and epicardium with saline before allowing blood to enter the suction system. This point deserves further investigation.

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