An in-vitro evaluation of aortic arch vessel perfusion characteristics comparing single versus multiple stream aortic cannulae

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Abstract

Objective: During extracorporeal circulation design and orientation of aortic cannulae tips mainly determine flow pattern in the aortic arch and arch vessels which is the objective of this in vitro study, comparing single versus multiple stream cannulae. Methods: In an aortic arch glass model, jet streams of 21–24 French aortic cannulae which were inserted in the ascending aorta were directed alternatively at the different arch vessels. Flows and pressures in the arch vessels were measured at pump flows of 3–6 l/min. Results: With optimal orientation of the jet stream in the aortic arch, no preferential flow in the arch vessels was seen. In the single jet stream aortic cannulae group a significant parallel increase in flow and pressure in the jet streamed arch vessels compared to the non-jet streamed arch vessels occurred (P < 0.05). With the jet stream directed on vessel 2 (left carotid vessel) there was a significant pressure and flow difference comparing the two non-jet streamed vessels with each other (P < 0.03). In the single stream 24 French cannulae the highest vessel pressure of 168 mmHg and an increase in flow of 186 ml/min was measured in the jet streamed left carotid artery at 6 l/min pump flow. The multiple stream cannulae provoked the highest vessel pressure of 106 mmHg in the corresponding jet streamed vessel and an increase in flow of 20 ml/min. Conclusion: Tip design of aortic cannulae and the orientation of its jet stream are potential sources of remarkable imbalance of arch vessel perfusion especially with single jet stream cannulae. These effects are more pronounced with single jet stream cannulae. These results may have important clinical implications regarding perfusion of arch vessels during extracorporeal circulation. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Aortic cannulae; Arch vessel perfusion; Hydrodynamics; Extracorporeal circulation; Cannulae tip design

1. Introduction

Atheroembolic events in the presence of ascending aortic atherosclerotic disease, inspired authors to evaluate different types of jet stream flow patterns of arterial cannulae, regarding exit velocity [1–3]. Atheroembolic dislodgement is partly explained by the high unphysiological jet flow exiting aortic perfusion cannulae [3,4]. Neurological deficits after open heart procedures are also subscribed to cerebral hemorrhage, global cerebral edema and cerebral hyperperfusion, that is largely unexplained in its origin [4–7]. There are several potential complications of ascending aortic arch cannulation, and arch vessel preferential flow, or inadvertent cannulation of the arch vessels are further complicative incidences not to be overlooked regarding their influence on neurological outcome [8–13]. Knowledge of the effects of aortic cannulae tip design and the orientation of the jet stream on arch vessel perfusion is scarce.

The purpose of this in-vitro study was to investigate arch vessel flow characteristics in a mock circulation, comparing single versus multiple jet stream aortic cannulae. The jet stream of the different cannulae was directed at the arch vessels alternatively mimicking an occasional clinical situation, of aortic arch vessel malperfusion during extracorporeal circulation.

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2. Materials and methods

2.1. Cannulae evaluated

2.1.1. Single jet stream cannulae:

2. Argyle\textsuperscript{TM} THI. Short tip angled. Model THI 591065, 22 Fr and model THI 591081, 24 Fr (Sherwood Medical St. Louis, MO, USA).
3. Research Medical.
   3.1. Model One: Short tip with side holes. ARS-022-C-HS, 22 Fr and ARS-024-C-HS, 24 Fr
   3.2. Model Two: Long tip with side holes. ARS-022-C-H, 22 Fr and ARS-024-C-H, 24 Fr

Since Parker \[7\] confirmed that no relevant flow occurred through the side holes of cannulae 1, 3.1, 3.2 these were grouped to the single stream cannulae (see Section 4).

2.1.2. Multiple jet stream cannula

4. 3M Sarns\textsuperscript{TM} Soft-Flow cannula. Angled short tip, with conus and lateral side holes. Model 3M SF 5761, 21 Fr and model 3M SF 6384, 24 Fr (3M Cardiovascular, Ann Arbor, MI, USA).

Freehand drawings of the different cannulae tip types are depicted in Fig. 1.

2.2. Experimental setup

A glass aortic arch model (inner diameter 22 mm) ratio 1:1, of an average adult size aortic arch was used. Its outlet was connected by a silicone tube (inner diameter 30 mm, outer diameter 35 mm and length 3 m) to an overflow reservoir 80 cm above the midlevel of the aortic arch. Thereby the mock circulation systemic pressure was set at 80 mmHg, measured at P4 (Fig. 2). From the overflow reservoir fluid drained by gravity into a hard-shell venous reservoir. The arch vessels had alternative inner diameters of 12 mm for vessel 1 (innominate artery), 8 mm for vessel 2 (left carotid artery) and 10 mm for vessel 3 (left subclavian artery), roughly simulating physiological diameter relationships, and each a length of 100 mm. Arch vessels were connected to a Harvey Bard cardiotomy reservoir, model H3700 (CR Bard, Tewsbury, MA, USA) with tubing inlet height at the same midlevel plane than that of the aortic arch model. Included 3 cm from the arch outlet of the three alternative

Fig. 1. Freehand drawing of the different types of aortic cannulae evaluated in this study (for numbers at cannulae see Section 2.1).
arch vessels were 3/8 to 3/8 inch luer lock connectors to facilitate vessel pressure measurement at points P1, P2 and P3 (Fig. 2). Immediately beyond the luer lock connectors, throttle valves partially occluded the tubing thereby setting the alternative arch vessel flows in accordance to the physiological flow distribution in the arch vessels at 80 mmHg systemic pressure and pump flows of 3, 4.5 and 6 l/min (Table 1). Extracorporeal components consisted of our clinically used tubing pack with 1/2 inch pump inlay tubing, a hard-shell oxygenator reservoir system Capiox, model CX*SX 18 R (Terumo, Tokyo, Japan) with an arterial filter Dideco, model D 734 (Dideco, Mirandola, Italy). A Caps roller pump, model 10-40-00 (Stöckert Instruments, Munich, Germany) circulated the volume. The pump was set occlusive at 250 mmHg, correcting the calibration for tubing used volumetrically. Pressure measurements were performed with pressure transducers, model P10EZ Statham® (Siemens, Fuerth, Germany) and a monitor, model Siemens-Sirecust 1260 (Siemens, Fuerth, Germany) continuously. The transducers were calibrated and zeroed before each series of measurements was performed. Arch vessel flow was measured continuously by Transonic ultrasonic system, model HT 207, and Transonic flow probes, model H2MB 508 (Transonic Systems, Ithaca, NY) at points F1, F2 and F3 (Fig. 2). The flow probes were calibrated for the tubing size (10 cm of 1/2 inch tube), the type of solution and temperature of solution. Prime solution consisted of a mixture of 60% water and 40% glycerin with a density of \( \rho = 1.09 \text{ g/cm}^3 \) (blood: \( \rho = 1.05-1.06 \text{ g/cm}^3 \)), and a viscosity of \( \eta = 4.0 \text{ mPa*s} \), (blood: \( \eta = 3-4 \text{ mPa*s} \)). The solution was maintained at a temperature of 20°C by the oxygenator heat exchanger.

For 21–22 Fr cannulae 3 and 4.5 l/min pump flows and for 24 Fr cannulae 4.5 and 6 l/min pump flows were chosen to accommodate clinical relevance. The site of cannulation was the convex circumference of the ascending aorta (Fig. 2). The preformed ledge on the cannulae (see Fig. 1) determined the depth of insertion of the cannulae. The distance of the cannulation site to vessel 1 was 3.5 cm, to vessel 2 was 4.5 cm and to vessel 3 was 6.0 cm. Pump flow was set and cannula jet stream was directed to flow optimally into the aortic arch without being directed to one of the arch vessels.

Table 1
Set flows of the alternative arch vessels

<table>
<thead>
<tr>
<th>Pump flow (l/min)</th>
<th>Innomonate artery Vessel 1 (15%) (ml/min)</th>
<th>Common carotis Vessel 2 (7.5%) (ml/min)</th>
<th>Left subclavian Vessel 3 (7.5%) (ml/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.00</td>
<td>450</td>
<td>230</td>
<td>230</td>
</tr>
<tr>
<td>4.50</td>
<td>680</td>
<td>340</td>
<td>340</td>
</tr>
<tr>
<td>6.00</td>
<td>900</td>
<td>450</td>
<td>450</td>
</tr>
</tbody>
</table>

Fig. 2. Aortic arch mock circulation: 1, vessel 1 (innominate artery); 2, vessel 2 (common carotid artery); 3, vessel 3 (left subclavian artery); 4, glass aortic arch; 5, aortic cannula; 6, overflow reservoir; 7, cardiotomy reservoir; 8, venous/cardiotomy reservoir; 9, roller pump; 10, oxygenator; 11, arterial filter; 12, throttle valves; 13, cannulation site. Arrows in the aortic arch indicate the different orientations of the aortic cannula jet stream. Arrows at the tubing lines indicate the flow direction.

Fig. 3. Flow pattern in the aortic arch and arch vessels with the jet of a single stream aortic cannula (24 Fr) directed at vessel 3 (right margin of the picture). The cannula is placed in the ascending aorta (left lower corner of the picture). Flow was visualized by illuminating air bubbles in the test fluid by laser light at 5 l/min pump flow.
Once this was accomplished, the cannula pressure gradient was determined by continuously measuring the pressure before the cannula and the systemic pressure at point P4 (Fig. 2). During this measurement the arch vessels were closed. Thereafter the arch vessels were opened to flow, and the aortic cannula jet stream was directed alternatively on the different arch vessels (Fig. 3) while measuring arch vessel pressure and flow of the jet streamed and non-jet streamed vessels continuously and simultaneously (Fig. 2). The desired jet streams on the alternative vessels were achieved once a maximum pressure was recorded and reproduced three times –2 mmHg being stable for 20 s each time.

Cannula inner diameter was measured with a caliper at the largest dimension, as cannulae are not fully circular. The measurements were repeated three times, and the mean value was taken. From this system the fluid was pumped through the oxygenator and arterial filter across the aortic cannula back into the aortic arch circulation.

2.3. Statistical analysis

The different single jet stream cannulae were grouped for each size. Differences in pressures and flows between the three arch vessels with this type of cannulae were analyzed by applying the Wilcoxon Test. (WinSTAT for Windows 3.0, Kalonia, Cambridge, MA). This test was chosen, as the measured values were not normally distributed. Thereby, the 1 percentile, 3 percentile and mean values were calculated. Compared were the flows and pressures between the two non streamed vessels and between the jet streamed vessel and the two non-jet streamed vessels at 3, 4.5 and 6 l/min pump flows. This was done for each of the three vessel jet stream orientations.

3. Results

Table 2 summarizes the values of aortic cannulae inner diameters, pressure gradients and arch vessel pressures and flow rates at 4.5 l/min pump flow for 21–22 Fr cannulae and at 6 l/min pump flow for 24 Fr cannulae. In the single stream 21–22 Fr cannulae group the highest vessel pressure of 158 mmHg was combined with an increased vessel flow of 30.6% (104 ml/min) above the set value with the jet directed at vessel 2 at 4.5 l/min pump flow. Also in the single 24 Fr cannulae group a highest jet stream pressure of 168 mmHg and an increased vessel flow of 41.3% (186 ml/min) above the set value was measured in directing the jet stream at vessel 2 at 6 l/min pump flow. The multiple jet stream 21 Fr cannulae also produced the highest vessel pressures of 106 mmHg and a vessel flow increase of 5.8% (20 ml/min) above the set value whilst jet streaming vessel 2 at 4.5 l/min pump flow. The 24 Fr multiple stream cannulae reached the highest vessel pressure of 98 mmHg and an increase in flow above normal set value of 6.4% (58 ml/min), however in jet streaming of vessel 1, at 6 l/min pump flow. The multiple jet stream cannulae clearly produced lower increases of vessel pressures and flows compared to the single jet stream cannulae. Inner diameters of cannulae groups varied largely (Table 2).

Fig. 4 shows the significant difference in vessel pressures between the jet streamed versus the two non-jet streamed vessels whilst jet streaming vessel 1. The two non-jet streamed vessels compared to each other showed no significant differences. The only exception is the significant pressure difference comparing the two non-jet streamed vessels 1 and 3 (P < 0.03), whilst jet streaming vessel 2. Only the results of vessel 1 are presented, as in case of orientating the jet at vessels 2 and 3, results were parallel.

Fig. 5 shows the significant difference in vessel pressures between the jet streamed versus the two non-jet streamed vessels whilst jet streaming vessel 1. The two non-jet streamed vessels compared to each other showed no significant differences. The only exception is the significant pressure difference comparing the two non-jet streamed vessels 1 and 3 (P < 0.03), whilst jet streaming vessel 2. Only the results of vessel 1 are presented, as in case of orientating the jet at vessels 2 and 3, results were parallel.
Fig. 5 shows the differences of vessel flow whilst jet streaming vessel 1, which parallels the results of the pressure differences, with significant flow increase comparing the jet streamed vessel to the two non-jet streamed vessels. Comparing the two non-jet streamed vessels to each other, no significant differences in vessel flows were measured, with exception of jet streaming of vessel 2. Multiple jet stream cannulae had a more balanced pressure and flow distribution in the arch vessels in comparison to the single stream cannulae.

4. Discussion

This study provides new information on the perfusion characteristics of the aortic arch vessels in dependence of the design and orientation of two types of aortic cannula tips during extracorporeal circulation. In contrast to multiple jet stream cannulae we have found a significant imbalance of perfusion in the different arch vessels with single jet stream cannulae if the jet stream was directed at one of the three vessels. These observed flow characteristics are subscribed to the Coanda effect, which is an application of the Bernoulli principle, describing the tendency of a jet stream to adhere to the boundary wall [9]. As the jet velocity increases, so does the lateral pressure drop, leading to decreased flow in the non streamed vessels. Especially those cannulae with small inner diameters and high pressure gradients lead to significant differences in the perfusion of the arch vessels, indicating a stronger jet formation.

Several authors assumed since the early days of cardiac surgery that aortic cannulation may lead to undesirable preferential flow of the arch vessels [7–16]. Therefore Parker in 1969 developed a multiple jet stream cannula, basket shaped, dividing the single jet stream in four jet streams. Several limitations of this study must be taken into consideration. The rigid glass model in our set-up has no elastic properties in order to simulate the ‘Windkessel’ effect as occurs in the normal elastic human aorta. This probably He already discovered that cannulae tip design is one of the main determinants of cannulae jet flow pattern that could avoid imperfect aortic arch perfusion [7]. Malperfusion of the arch vessels during extracorporeal circulation as identified clinically was regarded as a potential cause of deteriorated neurological outcome. Kulkarni in 1968 reported the case of a young girl with significant malperfusion of the arch vessels resulting in cerebral hemorrhage and death [7–16]. Besides these potential problems caused by cannula jet stream were also mentioned resulting atheroembolic dislodgement [2,3]. To overcome these disadvantages new tip designs of aortic cannulae were introduced into clinical practice especially regarding side holes in the tip with and without closed ends [2,3]. Open tip cannulae with side holes are not effective in dispersing the jet stream since 95% of flow passed through the open tip [7]. At higher flow rates we observed that fluid was even sucked through these side holes from the surrounding area into the cannula caused by the Venturi effect. If the open end of the tip was closed by a conus, cannula number 4 (Fig. 1), we observed that side holes proved to be effective significantly reducing the malperfusion of the aortic arch vessels. This phenomenon occurs, however, at the price of an increased pressure drop especially in smaller size cannulae. For example the 21 Fr multiple stream cannula produced a high pressure drop of 156 mmHg at 4.5 l/min in our study. Thereby damage of blood elements may be caused. Brodmann et al. who evaluated 29 different cannulae concerning pressure gradients concluded that a pressure gradient above 100 mmHg across the arterial cannula leads to excessive damage of blood elements [17].

Table 2

<table>
<thead>
<tr>
<th>Cannula type and model</th>
<th>Inner diameter (mm)</th>
<th>Pressure gradient (mmHg)</th>
<th>Jet streamed vessel pressures (mmHg)</th>
<th>Jet streamed vessel flow (ml/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vessel 1</td>
<td>Vessel 2</td>
</tr>
<tr>
<td>1. Single stream cannula</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USCI 1965, 22 Fr</td>
<td>4.80</td>
<td>173</td>
<td>132</td>
<td>158</td>
</tr>
<tr>
<td>Argyle 21 Fr</td>
<td>4.90</td>
<td>114</td>
<td>129</td>
<td>142</td>
</tr>
<tr>
<td>ARS-022-C-H, 22 Fr</td>
<td>5.30</td>
<td>95</td>
<td>132</td>
<td>140</td>
</tr>
<tr>
<td>ARS-022-C-HS, 22 Fr</td>
<td>5.50</td>
<td>84</td>
<td>128</td>
<td>123</td>
</tr>
<tr>
<td>ARS-221190 A, 22 Fr</td>
<td>6.10</td>
<td>57</td>
<td>115</td>
<td>116</td>
</tr>
<tr>
<td>USCI 1965, 24 Fr</td>
<td>5.20</td>
<td>187</td>
<td>139</td>
<td>168</td>
</tr>
<tr>
<td>Argyle, 24 Fr</td>
<td>5.70</td>
<td>152</td>
<td>141</td>
<td>155</td>
</tr>
<tr>
<td>ARS-024-C-H, 24 Fr</td>
<td>6.10</td>
<td>116</td>
<td>125</td>
<td>133</td>
</tr>
<tr>
<td>ARS-024-C-HS, 24 Fr</td>
<td>5.50</td>
<td>106</td>
<td>134</td>
<td>119</td>
</tr>
<tr>
<td>ARS-241190 A, 24 Fr</td>
<td>6.80</td>
<td>57</td>
<td>109</td>
<td>108</td>
</tr>
<tr>
<td>2. Multiple stream cannula</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3M SF, 5761, 21 Fr</td>
<td>5.10</td>
<td>156</td>
<td>104</td>
<td>106</td>
</tr>
<tr>
<td>3M SF, 6384, 24 Fr</td>
<td>6.10</td>
<td>57</td>
<td>98</td>
<td>91</td>
</tr>
</tbody>
</table>

Values of 21–22 Fr cannulae is at 4.5 l/min pump flow and 24 Fr cannulae at 6 l/min pump flow.
leads to higher pressures than in normal physiological vessels. Furthermore the throttle valves at the arch vessels that roughly simulate a static resistance were set constant. These conditions do not simulate the complex cerebral autoregulation that might influence flow characteristics of the arch vessels. These perfusion properties will become even more complex if carotid artery stenosis is present as often occurs in older patients with coronary artery disease. Also variances in systemic resistance which was also set constant in this study may significantly alter flow characteristics in the aortic arch.

Nevertheless these results indicate that malperfusion of arch vessels during extracorporeal circulation may occur as discussed in several clinical reports. Thus special attention should be paid on the balance of aortic arch vessel perfusion, that might be impaired by the orientation of the tip of single stream aortic cannulae at one of the arch vessels. Furthermore should one be aware of the aforementioned flow characteristics when interpreting cerebral perfusion during extracorporeal circulation. Construction and evaluation of novel tip designs of aortic cannulae that avoid excessive jet stream formation without increasing the pressure drop are highly desirable.

References