Unequal pressure distribution along the jaws of currently available vascular clamps: do we need a new aortic clamp?

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ABSTRACT

OBJECTIVES: The pressure along vascular clamp jaws may be unequally distributed, with greater pressure near the clamp hinge than at its top. Such unequal pressure distribution may cause aortic injury, especially in large aortas. We evaluated pressure distribution along different currently available clamp jaws.

METHODS: Seven descending thoracic aortas from pigs (diameter 2.0–3.0 cm) were plainly dissected and all side arteries closed. Aortas were filled up with water and cross-clamped. The pressure inside the aorta was raised to 100 mmHg and the aorta was clamped so tightly that no water exited from the distal aortic end. Each aorta was clamped seven times at different sites with the following clamps: DeBakey, Satinsky, femoral, iliac, Chitwood, angled handle Fogarty and straight handle Fogarty. The pressure along the clamp jaws was measured with a pressure-detecting film placed between the clamp jaws and aorta. The collagen-fibre disorganization was examined in haemotoxylin–eosin- and Elastica van Gieson-stained tissue samples.

RESULTS: The DeBakey clamp revealed the lowest maximum pressure along the clamp jaws after complete aortic occlusion (1.43 ± 0.49 MPa), whereas the Chitwood clamp’s pressure was the highest (3.26 ± 1.93 MPa, P < 0.001). The angled handle Fogarty clamp displayed the lowest difference between maximum pressures across the jaws (33%), with the greatest difference measured in the iliac (72%) and Chitwood (66%) clamps. The highest collagen-fibre disorganization score was observed in the proximal-to-the-clamp-hinge quartile after clamping with the angled handle Fogarty (2.8 ± 0.4), straight handle Fogarty (2.3 ± 0.8) and Chitwood (2.3 ± 0.5) clamps.

CONCLUSIONS: The pressure along clamp jaws is unequally distributed in all the currently available vascular clamps. The Chitwood clamp is associated with the highest maximum pressure during complete aortic occlusion and with the most unequal pressure distribution along the jaws.

Keywords: Aortic dissection • Aortic rupture • Cross-clamping

INTRODUCTION

Aortic clamping carries the risk of intimal damage, local dissection potentially leading to aortic dissection type A, the dislodgement of atheromatous material and aortic plaque rupture [1, 2]. These complications, although infrequent in published series [3, 4], lead to intra- and postoperative morbidity and mortality. In the contemporary literature, the incidence of iatrogenic aortic dissection during cardiac surgery is 0.06–0.23% with the entry tear usually observed at the site of aortic cannulation or cross-clamping [3].

The pressure along aortic clamp jaws is unequally distributed and is larger near the clamp hinge than at its top [5, 6]. Unequal pressure distribution requires a greater total clamp force to close the aorta than would be necessary were the pressure distributed equally across the clamp. Cross-clamping with the aortic clamps currently available may injure the aorta, especially large ones (Fig. 1), or those of patients with connective tissue disorders. We evaluated pressure distribution along the various currently available clamp jaws.

MATERIALS AND METHODS

Pressure measurement

Seven descending thoracic aortas (diameter 2.0–3.0 cm) were plainly dissected from pigs (80–100 kg) freshly sacrificed at a local abattoir. All small side arteries were ligated. The proximal aortic
end was connected to the Sterofundin BG 5 500-ml infusion bag (B. Braun Melsungen AG, Melsungen, Germany). The pressure inside the aortas was regulated using a pressure-infusion bag cuff and controlled by the SUPERTORQUEM5F pressure detection system (Johnson & Johnson Medical GmbH, Norderstedt, Germany) inserted through one of the spinal arteries.

We investigated the following vascular clamps (Fig. 2):

(i) DeBakey (Gebrüder Martin GmbH&Co.KG, Tuttlingen, Germany)
(ii) Satinsky (Gebrüder Martin GmbH&Co.KG, Tuttlingen, Germany)
(iii) Femoral (Gebrüder Martin GmbH&Co.KG, Tuttlingen, Germany)
(iv) Iliac (Aesculap AG, Tuttlingen, Germany)
(v) Chitwood (GEISTER Medizintechnik GmbH, Tuttlingen, Germany)
(vi) Straight handle Fogarty (A 3219, Applied Medical, Rancho Santa Margarita, CA, USA)
(vii) Angled handle Fogarty (A 3213, Applied Medical, Rancho Santa Margarita, CA, USA).

Each aorta was cross-clamped seven times with different clamps at different sites. A pressure-detecting film (FUJI PRESCALE FILM, Fujifilm Europe GmbH, Düsseldorf, Germany) was placed between clamp jaws and aorta. As soon as the aorta was clamped using the first two or three cogs, the pressure was raised to 100 mmHg and it was then clamped more tightly till no leakage at the distal aortic end was observed. Once the aorta was completely occluded, it remained clamped for 2 min. The pressure-detecting film was scanned with an Epson V37 scanner (Seiko Epson Corporation, Nagano, Japan) and evaluated using the software FUJIFILM Pressure Distribution Mapping System for PRESCALE, FPD-8010E Version 2.01 (Fujifilm Europe GmbH). An example of scanned pressure-detectable film is illustrated in Fig. 3. The clamped aortic segments were divided into four quartiles (proximal, middle proximal, middle distal and distal to the clamp hinge). The maximum pressure required in each section was measured.

Histological evaluation

Three additional aortas were filled with Sterofundin up to 100 mmHg and then clamped with each of the clamps described above, but for 2 h and without the pressure-detecting film, to obtain tissue for histology. The tissue samples were processed for light microscopy and embedded in paraffin. Samples were cut in 3-µm-thick sections perpendicular to the aortic wall and stained with haemotoxylin–eosin and Elastica van Gieson. The tissue damage was evaluated according to the collagen-fibre disorganization score using the 3-point scale as follows (Fig. 4):

(i) One point—great majority of collagen fibres are oriented parallel to one another and reveal a uniform architecture
(ii) Two points—about half of the collagen fibres are fragmented and not oriented parallel to one another

Figure 1: Local dissection after ascending aortic cross-clamping in a 62-year old patient undergoing aortic root, ascending and hemi-arch replacement for 5.8-cm proximal aortic aneurysm. Aortic wall lesion (shown with a forceps) was observed at the aortic area most proximal to the aortic clamp hinge.

Figure 2: Investigated vascular clamps: DeBakey (A), Satinsky (B), femoral (C), iliac (D), Chitwood (E), straight handle Fogarty (F) and angled handle Fogarty (G).
Three points—more than half of the collagen fibres are fragmented and not oriented parallel to one another

Statistical analysis

Continuous variables are summarized as means and standard deviation. For comparison of continuous variables, the Mann–Whitney rank-sum test was employed using IBM SPSS Statistics 22 (IBM Corporation, Armonk, NY, USA).

RESULTS

Maximal pressure along the clamp jaws

The lowest maximum pressure along the clamp jaws after complete aortic occlusion was measured in the DeBakey clamp (1.43 ± 0.49 MPa); this was lower than the pressure measured in the Satinsky ($P = 0.069$), iliac ($P = 0.007$) and Chitwood ($P = 0.003$) clamps. The highest maximum pressure was observed after clamping with the Chitwood clamp (3.26 ± 1.93 MPa; Fig. 5).

Pressure distribution along the clamp jaws

The pressure along the clamp jaws was unequally distributed in all the clamps. The most homogeneous distribution was observed in the angled handle Fogarty clamp, as it revealed the lowest difference (33%) between the highest and lowest maximum pressures measured at the four quartiles. We observed the greatest difference between maximum pressures across the clamp in the iliac (72%), and Chitwood (66%) clamps (Fig. 6).

Collagen-fibre disorganization after cross-clamping

We observed the architectural disorganization of collagen fibres after 2 h of aortic cross-clamping with each clamp. The highest average collagen-fibre damage score was observed in the proximal-to-the-clamp-hinge quartile after clamping with the angled handle Fogarty (2.8 ± 0.4), straight handle Fogarty (2.3 ± 0.8) and Chitwood (2.3 ± 0.5) clamps. The Chitwood clamp displayed the largest difference between collagen-fibre damage scores at the proximal and distal quartiles (proximal 2.3 ± 0.5, distal 1.3 ± 0.5; Fig. 7).

DISCUSSION

Aortic clamping is an activity that cardiac and vascular surgeons perform routinely, usually several times a day. Specific aortic clamps have been developed to accommodate (i) specific aortic segments, (ii) certain accesses to the aorta, (iii) the presence of atherosclerosis and (iv) aortic size. Although it is well known that aortic cross-clamping entails a certain degree of risk of iatrogenic tissue damage resulting in immediate or later aortic dissection or...
rupture, few studies have been conducted to define the limitations of currently available vascular clamps, to examine factors related to the trauma from aortic clamping, to design a new, less traumatic clamp, or to suggest the modification of currently available clamps [2, 5, 6]. Endovascular balloons are used for certain indications, but they have not found general acceptance due to various associated complications and economic factors [7, 8]. In our centre, we use the DeBakey clamp (Gebrüder Martin GmbH & Co. KG, Tuttlingen, Germany) for standard cardiac and aortic procedures; the Fogarty clamp with its softer insert surface is used for better conformity to the aorta’s texture (Applied Medical, Rancho Santa Margarita, CA, USA) in case of atherosclerosis, aneurysm or in patients with connective tissue disorders. We use the Chitwood clamp (GEISTER Medizintechnik GmbH, Tuttlingen, Germany) for minimally invasive mitral valve surgery.

During the last 6 months, we have experienced one immediate aortic dissection in one patient (Fig. 1) and one late contained aortic rupture 2 months after descending thoracic aortic replacement in one patient, both due to aortic cross-clamping at the initial surgery. The scope of our experimental study was to measure the pressure distribution along the vascular clamp jaws, since in both of the aforementioned patients we observed the aortic wall injury in the aortic area most proximal to the aortic clamp hinge, where the clamp force is the greatest [5, 6]. For this purpose, we used pressure-detectable films that enabled us to very precisely measure the clamping pressure at each point along the cross-clamped aorta.

The pressure over the clamp was distributed equally in none of the vascular clamps we analysed. The highest maximum pressure was observed after clamping with the Chitwood clamp in the area proximal to the clamp hinge. This clamp seems to carry a high risk of the ‘scissors’ effect. Its design—with short clamp jaws and hence, a short distance between clamp hinge and top—results in a large difference between the force generated at the proximal and distal sites. Clamping aortas that fit the jaws of clamps should be completely avoided because the force generated near the hinge in such a case is very high. Using the Chitwood clamp with its long jaws and not clamping large aortas with it reduces the risk of aortic injury due to the ‘scissors’ effect.

<table>
<thead>
<tr>
<th>DeBakey</th>
<th>SH Fogarty</th>
<th>AH Fogarty</th>
<th>Femoral</th>
<th>Satinsky</th>
<th>Iliac</th>
<th>Chitwood</th>
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<td>Prox.</td>
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<tr>
<td>Dist.</td>
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<td>2.2±1.0</td>
<td>2.0±0.9</td>
<td>2.0±0.6</td>
<td>1.8±0.4</td>
<td>2.2±0.8</td>
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Figure 5: Maximum pressure along the clamp jaws after complete aortic occlusion. SH: straight handle; AH: angled handle.

Figure 6: Maximum clamping pressure generated at proximal, middle proximal, middle distal and distal areas to the clamp-hinge quartiles. Pressure in the proximal quartile is 100% for each clamp. The proximal quartile is near, the distal quartile far from the clamp hinge. R: ratio between the highest and lowest pressure measured along the clamp jaws; SH: straight handle; AH: angled handle.

Figure 7: Collagen-fibre damage after 2-h aortic cross-clamping. Aortic samples were evaluated according to the 3-point collagen-fibre disorganization score.
The angled handle Fogarty clamp revealed the most even pressure distribution observed. However, the difference between the highest and lowest maximum pressures measured at four quartiles was >30% even in this clamp. We had employed the angled handle Fogarty clamp in both of the aforementioned patients who suffered aortic injury due to cross-clamping, since we knew they were at a higher risk having such large aortic diameters. In both of them, the clamped aortic segment diameter was >5 cm and the aorta filled the clamp at a distance of >8 cm. According to the law of the lever, cross-clamping a large aorta triggers a large difference between the stress at the proximal and that distal to the clamp-hinge aortic areas. Even the least trauma-causing, currently available aortic clamp can lead to serious, potentially lethal aortic injuries in such patients.

Several studies have addressed the influence of clamping pressure on peripheral vessels [2, 9, 10]. Their results suggest a threshold for histological injury following cross-clamping. In particular, endothelial lesions have been observed after only 1 min of clamping [2]. This indicates that endothelial tissue lesions due to aortic cross-clamping cannot be avoided, even if the cross-clamping is minimal (just enough). In our study, we observed disorganized collagen-fibre architecture after 2-h cross-clamping in conjunction with every vascular clamp we tested. The most severe damage was observed after clamping with the angled handle Fogarty, straight handle Fogarty and Chitwood clamps in the proximal-to-the-clamp-hinge aortic area, where clamp pressure is the greatest. While the collagen-fibre architectural changes correlated well with pressure distribution in the Chitwood clamp, they did not mirror the stress distribution in the angled handled Fogarty clamp, which displays the most even force distribution but yielded the highest collagen-fibre damage score among the clamps we analysed. One explanation for this might be the softer insert surface (used to enhance conformity) that only the Fogarty clamps have, which might in turn lead to more damage at the cellular level.

Limitations

Our study has two limitations. Firstly, the porcine aortas used in these experiments were harvested from healthy animals and were smaller in diameter than those usually clamped in the operating room. Secondly, our data on the collagen-fibre disorganization was limited by the small sample numbers, thus it was not possible to make definitive conclusions.

CONCLUSIONS

The pressure along the clamp jaws is distributed unequally in all the vascular clamps currently on the market. The Chitwood clamp is associated with the highest maximum pressure during complete aortic occlusion and with the most pronounced difference between the collagen-fibre damage score in the aortic areas proximal and distal to the clamp hinge. The most homogeneous distribution was observed in the angled handle Fogarty clamp. A new aortic clamp with a homogeneous distribution of the clamping force may decrease the incidence of iatrogenic aortic injury.

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Conflict of interest: none declared.

REFERENCES