Temporary caval stenting improves venous drainage during cardiopulmonary bypass

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Abstract

Objectives: Assess the benefit of temporary caval stenting for remote venous drainage during cardiopulmonary bypass (CPB). Methods: Temporary caval stenting was realized in bovine experiments (65 ± 6 kg) by the means of self-expanding (18F for insertion, 36F in situ) venous cannulas (Smartcanula LLC, Lausanne, Switzerland) with various lengths: 43 cm, 53 cm, 63 cm vs. a standard 28F wire armed cannula in trans-jugular fashion. Maximal blood flows were assessed for 20, 25 and 30 mmHg of driving pressure with a motorized table head height adjustment system. In addition, the inferior caval diameters (just above its bifurcation) were measured in real time with intravascular ultrasound (IVUS). Results: Venous drainage (flow in l/min) at 20 mmHg, 25 mmHg, and 30 mmHg drainage load was 3.5 ± 0.5, 3.7 ± 0.7 and 4.0 ± 0.6 for the 28F standard vs. 4.1 ± 0.7, 4.0 ± 1.3 and 3.9 ± 1.1 for the 36F smart 43 cm, vs. 5.0 ± 0.7, 5.3 ± 1.3 and 5.4 ± 1.4 for the 36F smart 53 cm, vs. 5.2 ± 0.5*, 5.6 ± 1.1* and 5.8 ± 1.0* for the 36F smart 63 cm. The inferior vena caval diameters at 30 mmHg were 13.5 ± 4.8 mm for 28F standard, 11.1 ± 3.6 for 36F smart 43 cm, 11.3 ± 3.2 for 36F 53 cm, and 17.0 ± 0.1* for 36F 63 cm (*P<0.05 for 28F standard vs. 36F smart 63 cm long). Conclusions: The 43 cm self-expanding 36F smartcanula® outperforms the 28F standard wire armed cannula at low drainage pressures and without augmentation. Temporary caval stenting with long self-expanding venous cannulas provides even better drainage (+51%).

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1. Introduction

Inadequate venous drainage during cardiopulmonary bypass has many drawbacks [1]. As a matter of fact, the amount of venous blood drained from the patient not only determines the pump flow that can be achieved during cardiopulmonary bypass (CPB) and is crucial for adequate end organ perfusion, but also defines the amount of blood that stays in the patients cardio-vascular system during the procedure. Hence, in addition to superior perfusion, improved venous drainage has also the potential to simplify the surgical procedure [2]. Considering the on-going trend towards minimal access procedures, the latter aspect is of prime interest [3].

There are numerous factors that can influence the quality of venous drainage during CPB including venous cannula design, venous cannula positioning, pump set-up etc. [1]. For remote venous cannulation (i.e. trans-femoral or trans-jugular) long thin walled, rectilinear venous cannulas are traditionally used in conjunction with a centrifugal pump or vacuum for augmentation of flow [3, 4]. In this setting, the multi-orifice cannula tip is usually positioned in the right atrium and the entire blood flow has to travel through the long and relatively narrow cannula lumen, which is essentially a function of the access vessel diameter [5]. Unfortunately, only about 90% of the theoretical target pump-flow can be achieved with this technique [6, 7].

However, full flow can be achieved without augmentation of venous drainage if better cannula designs are used as we have previously demonstrated for the smartcanula®, which is based on the ‘collapsed insertion and expansion in situ’ principle [8–11]. With its self-expanding open wall design, the vein itself providing the seal, this device acts also as a spacer preventing the vein from collapsing, and therefore allows all collateral blood to be drained directly towards the pump oxygenator.

The present study was designed to assess the potential benefit of temporary caval stenting with short (Fig. 1) vs. long (Fig. 2) self-expanding cannulas for remote venous drainage during cardiopulmonary bypass (CPB) with various drainage loads (Fig. 3).
ventilator parameters as a function of arterial and venous blood gas analyses drawn at regular intervals. Standard monitoring included continuous arterial oxygen saturation, exhaled CO₂ concentration, EKG, central venous and arterial blood pressures, as well as continuous measurement of the diameter of the distal vena cava by intravascular ultrasound (Clear View, Boston Scientific).

2.2. Cardiopulmonary bypass

CPB was established through a cervicotomy for remote (jugular vein and carotid artery) cannulation of the right atrium and the caval axis, respectively. The tubing set included a 1½” venous line, a hard shell venous reservoir, a state of the art integrated heat-exchanger/hollow-fiber oxygenator, and a ¾” arterial line with a 25 µm arterial filter. Clear priming (1500 ml) and full systemic heparinization (heparin loading dose 300 IU/kg body weight, heparin priming dose 5000 IU/l of priming fluid: ACT > 480 s) were used throughout the procedure.

2.3. Scenarios studied

Maximal stable pump flow, which is directly related to venous drainage without augmentation, was assessed for remote trans-jugular cannulation of the right atrium/vena cava with standard venous cannulae (43 cm long, wire armed, lighthouse tip design, 28F, dlp, Medtronic) vs. self-expanding venous cannulae (43 cm, 53 cm and 63 cm long, smartcanula®, 18F collapsed for insertion and 36F expanded in situ: Smartcanula LLC, Lausanne, Switzerland) for various table heights. The driving pressure difference or so-called drainage load [11] was measured in mmHg as the pressure difference between the level of the right atrium and the blood level in the hard shell venous reservoir. For this purpose, a pressure transducer was positioned at the level of the right atrium and the end of the connected pressure line was positioned at the target blood level in the venous hard shell reservoir. Three different drainage loads (20 mmHg, 25 mmHg and 30 mmHg) were studied with the help of a motorized table height adjustment system three times for each cannula. Likewise, the inferior vena caval diameters (1 cm above the caval bifurcation) were measured after stabilization of the blood flow with intravascular ultrasound: IVUS [12]. After obtaining a complete data set for a specific cannula, the animals were weaned from CPB and the venous cannula was replaced in random fashion, and CPB was resumed as described above. All cannulas were studied in all animals.

2.4. Statistical analyses

Mean ± S.D. was derived for continuous variables. Paired Student’s t-test (comparison of the surface under the curve) and two-way ANOVA were used for comparison between groups where applicable.

3. Results

Venous drainage (flow in l/min) at 20 mmHg, 25 mmHg and 30 mmHg drainage load was 3.5 ± 0.5, 3.7 ± 0.7 and 4.0 ± 0.6 for the 28F standard vs. 4.1 ± 0.7, 4.0 ± 1.3 and
At low drainage loads, the 43 cm smartcanula® outperforms the standard wire armed lighthouse tip cannula (non-linear fit and 95% confidence intervals).

3.9 ± 1.1 for the 36F smartcanula® 43 cm (Fig. 4) vs. 5.0 ± 0.7, 5.3 ± 1.3 and 5.4 ± 1.4* for the 36F smart 53 cm, vs. 5.2 ± 0.5*, 5.6 ± 1.1* and 5.8 ± 1.0* for the 36F smart 63 cm (Fig. 5; *P < 0.05 as compared to smart 43 cm). Obviously, the 43 cm self-expanding 36F smartcanula® outperforms the 28F standard wire armed cannula at low drainage pressures and without augmentation. However, temporary caval stenting with long self-expanding venous cannulas provides even far superior drainage (+51% in comparison to standard; P < 0.001 for standard vs. smart 63 cm, and P < 0.01 for standard vs. smart 53 cm).

A typical cross-section of the temporarily stented inferior vena cava obtained by intravascular ultrasound is shown in Fig. 6. The self-expanding venous cannula maintains the luminal width at the level of the IVUS probe. Fig. 7 displays the inferior vena caval diameters at 30 mmHg: 13.5 ± 4.8 mm for 28F standard, 11.1 ± 3.6 36F smart 43 cm, 11.3 ± 3.2 for 36F 53 cm, and 17.0 ± 0.1* for 36F 63 cm (*P < 0.05 for 28F standard vs. 36F smart 63 cm long).

4. Discussion

Unsurpassed venous drainage with gravity alone can be achieved by temporary stenting of the entire caval axis (superior vena cava, right atrium, and inferior vena cava) with the long self-expanding venous smartcanula®, which prevents the floppy venous wall from collapsing during CPB. We have previously demonstrated that self-expanding venous cannulas allow for superior venous drainage without augmentation in comparison to standard wire supported lighthouse tip cannulas [8] as well as traditional thin-walled percutaneous venous cannulas [13], and similar results have been shown for the clinical setting [14].

As expected, the 43 cm self-expanding 36F smartcanula® provided for the present setting better venous drainage (+17%) at low drainage loads (20 mmHg) and without augmentation than the 28F standard wire armed cannula (Fig. 4). The flow achievable with the self-expanding venous cannula at 20 mmHg drainage load could not be improved any further by increasing the table height and providing 25 mmHg drainage load and 30 mmHg, respectively. Obviously, the venous blood that could reach the...
cannula easily was drained directly to the venous reservoir already with 20 mmHg drainage load. In contrast, increasing the table height improved the venous drainage with the control cannula, indicating that the standard lighthouse tip cannula itself was limiting venous drainage, and that this problem linked to the pressure drop can be overcome up to some point by increasing the drainage load, i.e. the table height.

New is the fact, that longer self-expanding venous cannulas can provide better venous drainage than shorter ones. This is somewhat against traditional wisdom which implies, that longer cannulas have higher resistance and therefore lower flow or drainage capacity, respectively. The explanation for the phenomenon observed here is that longer traditional cannulas are in fact long narrow tubes, and therefore the resistance increases indeed in linear fashion with cannula length (Bernoulli’s law), at least as long as laminar flow patterns can be maintained.

In contrast, the self-expanding venous cannulas act only as somewhat restrictive narrow tubes for the first few cm within the access vessel (here the jugular vein). For the remainder of the vein (here the superior vena cava, the right atrium and the inferior vena cava), the self-expanding venous cannulas not only adapt to the larger venous diameter and are therefore less limiting the flow because of the superior mean cross-sectional area, but in addition allow for direct entrance of collateral blood inflow into the cannula lumen. Therefore, the full blood flow uses only the last few centimeters of the self-expanding cannula before it exits from the body, whereas elsewhere the cannula flow is only a fraction of the total blood flow. Again, this drainage pattern is very different from that observed in traditional percutaneous cannulas, where the entire blood flow has to pass through the narrow cannula lumen over its entire length.

The so-called open wall design of the smartcanula®, over the vast majority of its surface, has the additional advantage, that this self-expanding cannula can indeed be used as a temporary caval stent and thus allows to prevent the well known collapse of the vena cava (Fig. 6), which is a major limitation for efficient drainage as demonstrated by the fact that the longest self-expanding venous cannula (63 cm) used here, provides up to 51% more venous drainage/pump flow as compared to the short 43 cm version.

It has to be stressed that the technique for temporary caval stenting demonstrated here is fully reversible. As a matter of fact, a completely expanded 36F self-expanding cannula (the most frequently used size in adults) does not reach the natural diameter of the caval veins in adults which measure usually 60F or more. If it is true that the self-expanding cannula acts as a spacer during perfusion thus preventing the caval veins from collapsing, and therefore the venous wall indeed does touch the cannula, it has to be considered that this also happens with traditional cannulas at the cannula site as well as at the non-supported sites as demonstrated routinely by the so-called atrial chatter [9, 15].

An interesting observation is the fact that the diameter of the inferior vena cava measured above its bifurcation appears to decrease with improved venous drainage by almost 20% for 43 cm and 53 cm self-expanding cannulas as compared to the standard rectilinear lighthouse tip designs (Fig. 7). In contrast, there is a 25% increase in diameter in comparison to the 28F reference diameter for the 36F 63 cm self-expanding design (P<0.05), or a 54% increase with reference to the 36F 53 cm self-expanding design. This increase of the inferior caval diameter with the longest self-expanding cannula is due to the proximity of its proximity to the level of the measurement.

A different problem is the removal of the temporary caval stent. Fortunately enough this appears to be a minor issue. As a matter of fact, the self-expanding cannula is collapsed prior to insertion by stretching it with the corresponding mandrel. Likewise, gentle traction at decannulation results in elongation, and therefore reduces the diameter. This in turn makes the removal of the ‘temporary caval stent/self-expanding cannula’ less traumatic than what we are used to see with traditional rectilinear cannulas, which tend to stick to the vessel wall. It can be mentioned here that we withdraw the self-expanding cannulas completely stretched between two fingers positioned at the vascular entry site, in order to prevent the blood from exiting at the same time.

We conclude, that the described temporary stenting of the caval axis during CPB by means of the long self-expanding venous cannulas provides unmatched venous drainage up to 51% above the traditional values for the present setting. Gravity drainage with low drainage loads is sufficient by all means and augmentation with centrifugal pumps, vacuum or other adjuncts is not only unnecessary, but appears to be flow limiting. Similar results can be expected for the clinical setting where trans-femoral venous cannulation with self-expanding cannulas allows for temporary caval stenting of the inferior vena cava, the right atrium and the superior vena cava [14].

References


