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# Routine use of self-expanding venous cannulas for cardiopulmonary bypass: benefits and pitfalls in 100 consecutive cases<sup>☆</sup>

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## Abstract

**Objective:** Assess the performance of self-expanding venous cannulas for routine use in open-heart surgery. **Methods:** Prospective study in 100 unselected consecutive patients undergoing open-heart surgery with either remote or central smart venous cannulation. **Results:** The study focuses on the 76 consecutive adult patients (mean age  $59.2 \pm 17.3$  years; 60 males, 16 females) undergoing surgical procedures with total cardiopulmonary bypass for either valve procedures (42/76 patients = 55.3%), ascending aorta and arch repair (20/76 patients = 26.3%), coronary artery revascularization (13/76 patients = 17.1%) or other procedures (11/76 patients = 14.5%) with 14/76 patients (18.4%) undergoing redo surgery and 6/76 patients (7.9%) undergoing small access surgery. The mean pump flow achieved by gravity drainage alone accounted for  $5.0 \pm 0.6$  l/min (=114% of target) in the entire study population ( $n = 76$ ) as compared to the calculated, theoretical pump flow of  $4.4 \pm 0.5$  l/min ( $p < 0.0001$ ). For the femoral cannulation sub-group ( $n = 35$ ) pump flow achieved by gravity drainage alone accounted for  $4.9 \pm 0.6$  l/min (=114% of target) as compared to the calculated theoretical pump flow of  $4.3 \pm 0.4$  l/min ( $p < 0.0001$ ). The corresponding numbers for trans-subclavian cannulation ( $n = 7$ ) are  $5.2 \pm 0.5$  l/min (111%) for the pump flow achieved by gravity drainage as compared to the theoretical target flow of  $4.7 \pm 0.4$  l/min. For the central cannulation sub-group ( $n = 34$ ) mean flow achieved by gravity drainage with a self-expanding venous cannula accounted for  $5.1 \pm 0.7$  l/min (=116% of target) as compared to the calculated theoretical flow of  $4.4 \pm 0.6$  l/min ( $p < 0.0001$ ). **Conclusion:** Full or more than target flow was achieved in 97% of the patients studied undergoing CPB with self-expanding venous cannulas and gravity drainage. Remote venous cannulation with self-expanding cannulas provides similar flows as central cannulation. Augmentation of venous return is no longer necessary.

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**Keywords:** Cannulas; Self-expanding cannulas; Smart cannulation; Cardiopulmonary bypass; Perfusion; Heart lung machine; Reoperation; Open-heart surgery

## 1. Introduction

Cardiopulmonary bypass has been established more than 50 years ago, but little progress has been made at the interface between the vasculature of the body and the extracorporeal circulation. Although, the stainless steel cannulas from the early days were soon replaced by cannulas made from plastic with various tip and orifice designs, the main improvements were mainly made more than 20 years ago with the introduction of wire supported models having improved kink resistance, and consecutively, the development of thin wall designs which, in conjunction with a mandrel and a guide wire, can be used in percutaneous fashion [1,2]. However,

inadequate venous drainage during cardiopulmonary bypass with traditional cannulas is quite a common problem, and has a number of underestimated drawbacks including inadequate end organ perfusion, progressive hemodilution with consecutive transfusion of homologous blood products, and, last but not least, an operating field flooded with blood. The latter may not only make the surgical procedure more difficult, but requires more cardiotomy suction, which in turn increases blood trauma, and also activates inflammatory cascades.

A new generation of venous cannulas that can change its shape within the body [3] was originally designed for remote access perfusion where, by definition, the access vessel is smaller than the target vessel to be drained. Interestingly, there is increasing evidence, that venous cannulation relying on the 'collapsed insertion and expansion in situ' concept is not only beneficial in remote venous cannulation, where unmatched flow rates can be achieved with gravity drainage alone [4], but also for central cannulation [5,6]. The present study summarizes our recent experience with systematic use of self-expanding cannulas for both peripheral and central venous cannulation.

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Fig. 1. Self-expanding smart canula<sup>®</sup>:

- on the left straight configuration in a large orifice
- on the right, narrow orifice with respect to the diameter of the self-expanding cannula and consecutive diabolo-shape of the cannula.

## 2. Patients and methods

Self-expanding venous cannulas (Smart canula<sup>®</sup>, Smart-canula LLC, Lausanne, Switzerland: collapsed state <18 F, expanded state 36 F, connecting to 3/8 in. with five different lengths: 63 cm, 53 cm, 43 cm, 34 cm and 26 cm (Fig. 1) as a function of body size and procedure planned) were systematically used in 100 unselected, consecutive patients undergoing open-heart surgery using either remote or central cannulation sites for establishing cardiopulmonary bypass as a function of the procedures to be performed.

### 2.1. Cannulation techniques

#### 2.1.1. Femoral venous smart cannulation

The self-expanding cannulas studied are used in similar fashion as traditional percutaneous cannulas, i.e. in open, semi-open or percutaneous fashion [7]. After systemic

heparinization, the common femoral vein is punctured with a hollow needle. Once proper backflow (low pressure, de-saturated venous blood) is obtained, a J-type guide wire is introduced through the hollow needle into the common femoral vein, and the iliac veins into the caval axis (Fig. 2).

For transfemoral right atrial smart cannulation, the guide wire tip is brought into the superior vena cava, and its position is checked by transesophageal echocardiography (TEE). A self-expanding cannula corresponding to the distance between the access vessel and the target vessel is selected, collapsed (stretched with the corresponding mandrel), and inserted over the guide wire after using a

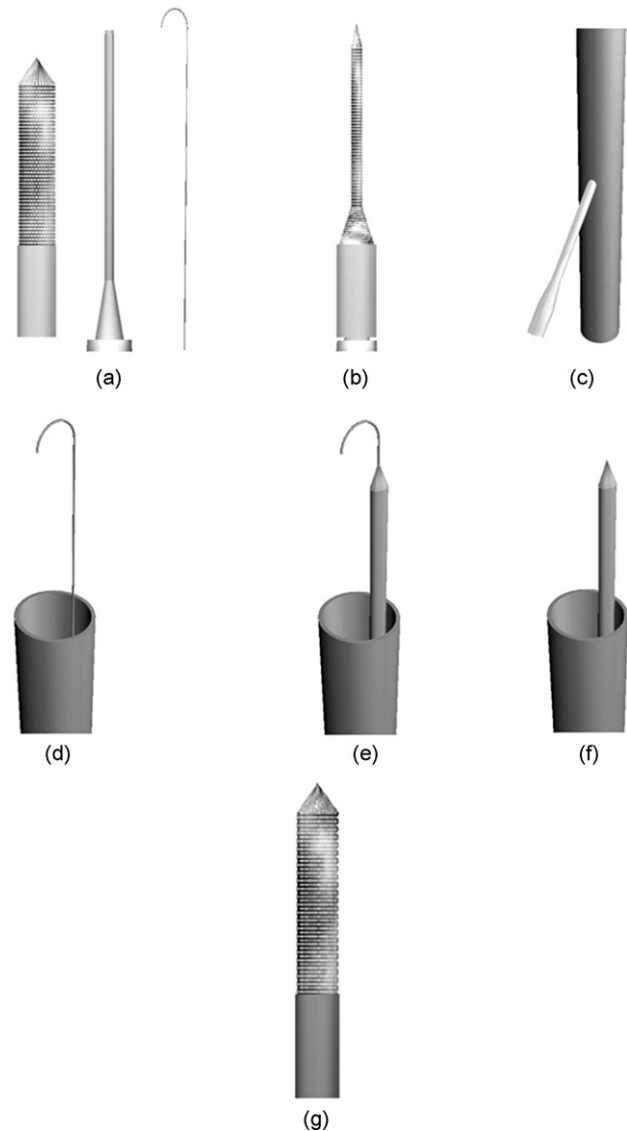


Fig. 2. Smart cannulation requires a self-expanding smart canula<sup>®</sup>, the corresponding mandrel (hollow), and a J-type guide wire (a). The self-expanding cannula is collapsed prior to insertion by stretching with the corresponding mandrel (b). Proper heparinization has to be checked prior to puncture or incision of the access vein (e.g. v. femoralis communis) (c). A J-type guide wire is inserted (e.g. transfemoral) and its tip position is checked with TEE (e.g. in the superior vena cava) (d). The collapsed (stretched) self-expanding cannula is inserted over the wire (e). The guide wire is removed first in order to prevent cannula tip dislocation (f). The mandrel is removed second and the smart canula<sup>®</sup> expands (g): check cannula position with TEE, debubble, and connect.

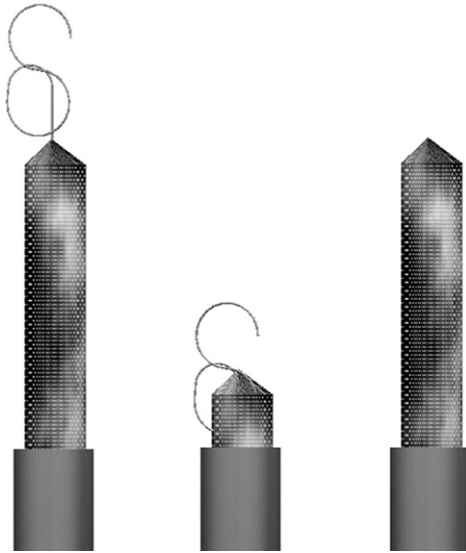


Fig. 3. Removal of kinked or curled guide wire (left) can lead to cannula tip dislocation (center). This can be avoided if the guide wire is removed first and the mandrel second (right). Note, the self-expanding cannula can be pulled back at any time. However, further advancement requires insertion of the mandrel for re-collapsing the device.

blade and/or a dilator. The right position of the cannula tip is checked with TEE. The guide wire is removed before the mandrel in order to prevent cannula tip dislocation (Fig. 3). The mandrel is removed, and proper expansion of the cannula is documented with TEE (Fig. 4) prior to debubbling and connection to the standard 1/2 in. venous line which is secured with a suture or a tape.

### 2.1.2. Subclavian venous smart cannulation

Subclavian venous cannulation is performed in similar open or semi-open fashion as outlined for femoral cannulation. After systemic heparinization, the prepared subclavian vein is punctured with a hollow needle through a purse-string suture, a guide wire is inserted and brought into the right

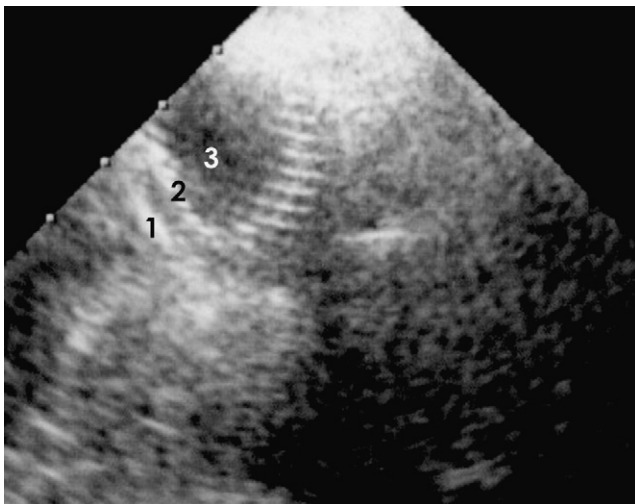


Fig. 4. Expanded smart canula<sup>®</sup> visualized in the vena cava close to the right atrium with TEE (with permission from 7): wall of the vena cava (1), metallic structure of the opened self-expanding cannula (2), and its lumen (3). Distance between markers on the upper left border represents 10 mm.

atrium and the inferior vena cava under control with TEE. A pre-curved guide wire or catheter is sometimes necessary to get around the angle between the subclavian vein and the superior vena cava. This angulation may also require a catheter for the exchange of a standard J-type wire for a super stiff guide wire prior to insertion of the collapsed (stretched with the corresponding mandrel) self-expanding cannula. As an alternative, transjugular access is more direct and easier, but for patients undergoing subclavian artery cannulation for aortic arch repair, an additional skin incision is required. Proper positioning of the cannula tip in the inferior vena cava is checked prior to removal of the guide wire (first) and the mandrel (second). A tie secures the armed cannula body with a loose snare of the purse-string suture prior to connection with the 1/2 in. venous line.

### 2.1.3. Central venous smart cannulation

A purse-string suture for a 30 F orifice (10 mm in diameter) is prepared below the right atrial appendage, the patient is heparinized, and the right atrium is punctured with a hollow needle. A guide wire with a large J (typically 15 mm in diameter) is inserted through the right atrium, deep into the inferior vena cava. The right atrial orifice is enlarged with a small dilator (15 F) or an instrument. The collapsed (stretched) self-expanding cannula is fed over the guide wire and inserted deep into the inferior vena cava under control with TEE. Some of the uncovered part and about half of the covered part (4 cm) are kept inside the right atrium in order to allow for both a good seal and optimized drainage of all affluent veins. A tie secures the armed cannula body with the almost open snare of the purse-string suture prior to connection with the 1/2 in. venous line.

## 2.2. Cardiopulmonary bypass

A standard perfusion set (1/2 in. venous line, 3/8 in. arterial line) with a hollow fiber membrane oxygenator, a hard shell venous reservoir with integrated cardiotomy reservoir, and an arterial filter are used in conjunction with a roller pump in routine fashion relying on gravity drainage alone in all cases. Neither vacuum nor a centrifugal pump is prepared. Target pump flow is 2.4 l/min m<sup>2</sup> with a hematocrit above 20%. Blood gases are drawn before and at regular intervals during perfusion for adjustment of the gas flows with gas blender. Target ACT is >480 s. Pump flow and/or hematocrit are increased if the venous oxygen saturation drops below 60%.

### 2.3. Data analyses

Feasibility of smart venous cannulation, technical problems, theoretical and maximal achievable flows in relation to the venous cannula used, are prospectively studied for each patient. Continuous variables are presented as mean  $\pm$  standard deviation. Student's *t*-test for paired or unpaired variables is used for comparison where applicable.

## 3. Results

This study population of 100 consecutive patients undergoing open-heart surgery by the same senior surgeon included

81 adult patients and 19 pediatric patients. The latter will be analyzed separately. Five patients required partial cardiopulmonary for proximal unloading and distal protection in descending thoracic and thoraco-abdominal aneurysm repair (3/5) or temporary mechanical circulatory support, and therefore this analysis focuses on the 76 consecutive adult patients (mean age  $59.2 \pm 17.3$  years; 60 males, 16 females) undergoing surgical procedures with total cardiopulmonary bypass for either valve procedures (42/76 patients = 55.3%), ascending aorta and arch repair (20/76 patients = 26.3%), coronary artery revascularization (13/76 patients = 17.1%) or other procedures (11/76 patients = 14.5%) with 14/76 patients (18.4%) undergoing redo surgery and 6/76 patients (7.9%) undergoing small access surgery. The mean pump flow achieved by gravity drainage alone accounted for  $5.0 \pm 0.6$  l/min (=114% of target) in the entire study population ( $n = 76$ ) as compared to the calculated, theoretical pump flow of  $4.4 \pm 0.5$  l/min ( $p < 0.0001$ ).

Peripheral cannulation was used in 42/76 patients (55.3%) relying on transfemoral access in 35/42 patients (83.3%: valves 21/35, aneurysms 6/35, coronary artery revascularization 4/35, other 8/35) as compared to trans-subclavian access in 7/42 patients (16.7%) for ascending aorta and arch repair. For the entire peripheral cannulation group ( $n = 42$ ), the pump flow achieved by gravity drainage reached again  $5.0 \pm 0.6$  l/min (=114% of target) as compared to the calculated theoretical pump flow of  $4.4 \pm 0.4$  l/min ( $p < 0.0001$ ). For the femoral cannulation sub-group ( $n = 35$ ) pump flow achieved by gravity drainage alone using self-expanding venous cannulas with a mean length of  $68 \pm 6$  cm accounted for  $4.9 \pm 0.6$  l/min (=114% of target) as compared to the calculated theoretical pump flow of  $4.3 \pm 0.4$  l/min ( $p < 0.0001$ ).

For the transfemoral cannulation group, cannula tip displacement as detected by TEE occurred in 1/35 patients. This cannula was withdrawn, the guide wire was reinserted and the collapsed (stretched) cannula re-positioned over the wire as described above.

The flow achieved with peripheral femoral cannulation as a function of cannula length is depicted in Fig. 5. For the patients cannulated with 53 cm self-expanding cannulas, the pump flow achieved by gravity drainage alone was

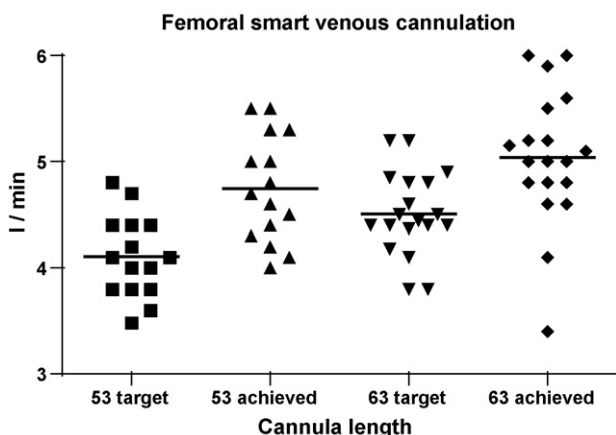


Fig. 5. Target flow and achieved flow for transfemoral smart cannulation: 115% of target flow was achieved by gravity drainage with the 53 cm long self-expanding cannula ( $p < 0.001$ ) and 111% of target flow was achieved by gravity drainage with the 63 cm long self-expanding cannula ( $p < 0.0005$ ).

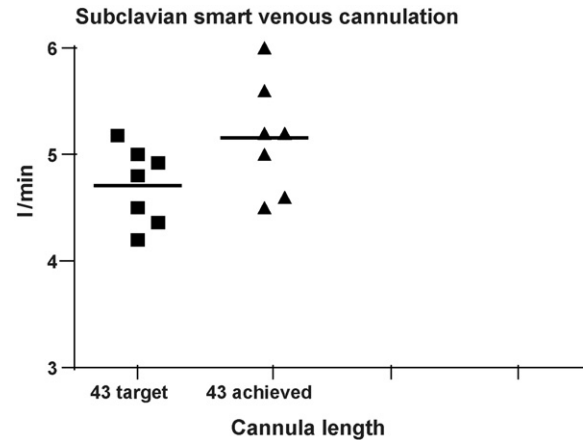


Fig. 6. Target flow and achieved flow for trans-subclavian smart venous cannulation with 43 cm long self-expanding cannulas: 111% of target flow was achieved by gravity drainage alone.

$4.7 \pm 0.5$  l/min (=115% of target) as compared to a calculated theoretical flow of  $4.1 \pm 0.4$  l/min ( $p < 0.001$ ). For the patients cannulated with 63 cm self-expanding cannulas, the pump flow achieved by gravity drainage alone was  $5.1 \pm 0.7$  l/min (=111% of target) as compared to a calculated theoretical flow of  $4.6 \pm 0.4$  l/min ( $p < 0.0005$ ).

The flow achieved with peripheral subclavian cannulation as a function of cannula length is depicted in Fig. 6. The seven patients in this sub-group undergoing ascending aorta an arch repair were all cannulated with 43 cm long self-expanding cannulas. However, in 2/7 patients, curved catheters and stiffer guide wires were necessary to navigate around the angle formed between the axis of the vena subclavia and the axis of the vena cava. The mean pump flow achieved by gravity drainage alone was  $5.2 \pm 0.5$  l/min (=111% of target) as compared to a calculated theoretical flow of  $4.7 \pm 0.4$  l/min ( $p = 0.0526$ ).

Central cannulation through the right atrium into the inferior vena cava was used in 34/76 patients for valve repair or replacement in 24/34, coronary artery revascularization in 11/34, aortic root and ascending aortic repair in 6/34, and other procedures in 2/34. Mean flow achieved by gravity drainage in the central cannulation group with a mean self-expanding venous cannula length of  $36 \pm 4$  cm accounted for  $5.1 \pm 0.7$  l/min (=116% of target) as compared to the calculated theoretical flow of  $4.4 \pm 0.6$  l/min ( $p < 0.0001$ ).

The flow achieved for central venous cannulation through a 30 F access orifice (10 mm in diameter) in the right atrium, and as a function of cannula length is depicted in Fig. 7. For the 34 cm self-expanding cannula mean flow achieved for gravity drainage alone accounted for  $4.9 \pm 0.5$  l/min (=114% of target) as compared to a calculated theoretical flow of  $4.3 \pm 0.5$  l/min ( $p < 0.0001$ ). For the 43 cm self-expanding cannula the mean flow achieved by gravity drainage alone accounted for  $6.0 \pm 0.8$  l/min (=122% of target) as compared to a calculated theoretical flow of  $4.9 \pm 0.8$  l/min ( $p < 0.05$ ). Interestingly enough, the comparison between the group drained by 34 cm long self-expanding cannulas vs the 43 cm long version was also highly significant ( $p < 0.0001$ ) in favor of the longer device.

Overall performance of venous smart cannulations is displayed in Fig. 8. As a matter of fact, there is a strong

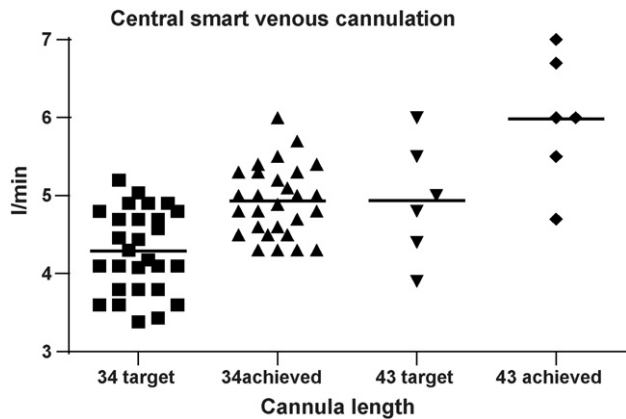


Fig. 7. Target flow and achieved flow for trans-atrial smart venous cannulation with 34 cm and 43 cm long self-expanding cannulas: 114% of target flow was achieved by gravity drainage with the 34 cm long self-expanding cannula ( $p < 0.0001$ ) and 122% of target flow was achieved by gravity drainage with the 43 cm long self-expanding cannula ( $p < 0.05$ ). Achieved flow with 34 cm vs 43 cm was in favor of the latter ( $p < 0.0001$ ).

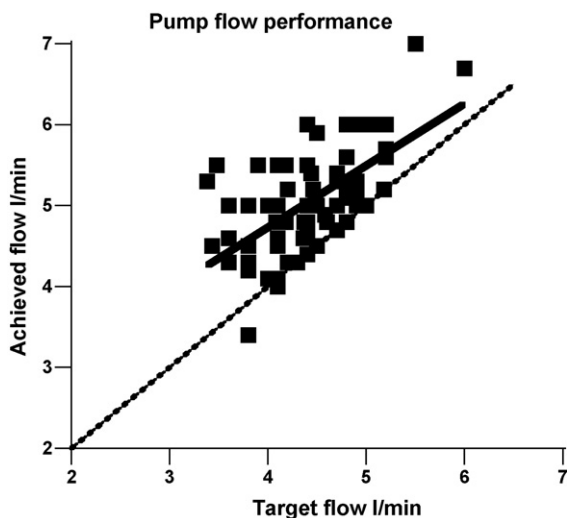


Fig. 8. Pump flow achieved by venous smart cannulation with gravity drainage alone as a function of calculated theoretical target flow of  $2.4 \text{ l/min m}^2$  in 76 consecutive adult patients: all values (mean 113%) are on or above the predicted reference line representing 100% target flow with the exception of 2/76 patients where 89% and 98% were reached, respectively.

correlation between the theoretically calculated target flows and the actually achieved pump flows using self-expanding venous cannulas in combination with gravity drainage. In 74/76 adult patients the pump flows achieved are on or above the predicted reference line representing 100% and accounts for 113% of the theoretical target. Only in 2/76 patients the target level was not reached and accounted for 89% and 98% respectively, flows that could be improved with standard measures (mainly additional volume).

#### 4. Discussion

Routine smart venous cannulation using self-expanding cannulas provides excellent flows for all, peripheral transfemoral as well as trans-subclavian remote venous cannulation

as well as single transatrial central venous cannulation with a small access orifice. Furthermore, remote venous cannulation with self-expanding cannulas provides similar flows as central cannulation. As a matter of fact the pump flows achieved in this consecutive series of adult patients are in 97% on or above target (mean 113%), and as a result, augmentation using centrifugal pumps or vacuum is unnecessary as previously reported for randomized experimental studies [3,8] and smaller series for specific indications [4,5,9]. It has also been shown previously in a study comparing self-expanding cannulas (access orifice 30 F) to classic two-stage cannulas (access orifice 48 F), that blood flows more than 10% above the target of  $2.4 \text{ l/m}^2$  can be achieved without additional blood trauma [6].

There are a number of reasons that explain the increased drainage capacity that can be achieved with the self-expanding smart canula<sup>®</sup> as compared to traditional rectilinear cannulas with augmentation [10,11]. These include:

- The superior mean effective cross-sectional area (usually more than the double of conventional percutaneous cannulas and also well above the minimal cross sectional area required for flows up to 6 l/min and more [11,12]).
- The unrestricted cannula tip orifices (larger by at least one order of magnitude).
- The reduced wall thickness (a fraction of traditional designs).
- The open wall design (allowing for drainage of collateral blood flow directly into the cannula almost over its entire intravascular length).

As outlined above, optimal drainage requires both the superior and the inferior vena cava to be kept open with a well positioned self-expanding cannula. This can be achieved with one long 36 F smart canula<sup>®</sup> inserted from the groin (femoral access: 63 cm for tall adults as shown in this study, 53 cm for smaller adults). Interestingly enough, the self-expanding smart canula<sup>®</sup> can also be inserted from the neck in transjugular or trans-subclavian fashion. However, image-guided optimization of the smart canula<sup>®</sup> tip positioned well within the inferior vena cava is helpful for optimized venous drainage. For proper placement of the smart canula<sup>®</sup> tip, it is important to proceed in stepwise fashion (Fig. 2) and e.g. for femoral remote cannulation to

- check with TEE the position of the guide wire within the superior vena cava before insertion of the collapsed smart canula<sup>®</sup> (stretched over the corresponding mandrel),
- follow with TEE the positioning of the tip of the smart canula<sup>®</sup> within the superior vena cava [13,14],
- remove the guide wire with the mandrel still in place, in order to prevent smart canula<sup>®</sup> tip migration (Fig. 3), and
- finally to monitor with TEE the expansion of the smart canula<sup>®</sup> during removal of the mandrel.

Although, full flow or more was being achieved in almost all patients with remote smart venous cannulation using the techniques described, it is important that a proper subcutaneous channel is prepared for the percutaneous approach. Use of dilators in sequential fashion up to 24 F is recommended. However, predilatation with the mandrel

supported arterial cannula over a guide wire prior to insertion of a venous cannula has been reported for traditional venous rectilinear cannulas [15], and is also effective with self-expanding venous cannulas.

Considering the growing number of indications for remote venous cannulation, which follows the development for small access open-heart surgery [16,17], as well as the growth of redo open-heart surgery [18,19], and other complex procedures [20,21], the advent of self-expanding venous cannulas is a major step forward in optimization of cardiopulmonary bypass. Better venous drainage with remote venous cannulation not only allows for higher pump flows and improved end-organ perfusion, but is also essential for a bloodless operative field, which in turn simplifies the surgical procedure. The smaller access orifice (less than half of the surface) required for smart central cannulation is of additional benefit for the surgeon and the patient.

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