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Damage control of caval injuries in a porcine model using a retrievable Rescue stent

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Abstract

Objective: Early hemorrhage control before the operating room is essential to reduce the significant mortality associated with traumatic injuries of the vena cava. Conventional approaches present logistical challenges on the battlefield or in the trauma bay. A retrievable stent graft would allow rapid hemorrhage control in the preoperative setting when endovascular expertise is not immediately available and without committing a patient to the limitations of current permanent stents. This study details a refined retrievable Rescue stent for percutaneous delivery that was examined in a porcine survival model of penetrating caval hemorrhage.

Methods: A retrievable caval stent was reduced in delivery profile to a 9F sheath using finite element analysis. The final stent was constructed with a “petal and stem” design using nitinol wire followed by covering with polytetrafluoroethylene. Seven Yorkshire pigs (79–86 kg) underwent 22F injury of the infrarenal vena cava with intentional class II hemorrhage (1200 mL). Percutaneous deployment of the Rescue stent was used to temporize hemorrhage for 60 minutes, followed by resuscitation with cell saver blood and permanent caval repair. Hemorrhage control was documented with photography and angiography. Vital signs were recorded and laboratory

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values were measured out to 48 hours postoperatively. Data were examined with a repeated-measures analysis of variance.

Results: The profile of the caval Rescue stent was successfully reduced from 16F to 9F while remaining within fracture and shape memory limits for nitinol. In addition, both rapid deployment and recapture were preserved. Following intentional hemorrhage after caval injury, animals revealed a significant drop in mean arterial pressure (average, 30 mm Hg), acidosis, and elevated lactate level compared with before injury. Compared with uncontrolled hemorrhage, which resulted in death in <9 minutes, the Rescue stent achieved hemorrhage control in <1 minute after venous access in all seven animals. All animals were successfully recovered after permanent repair. There was no significant change in levels of transaminases, bilirubin, creatinine, or hemoglobin at 48 hours compared with preinjury baseline.

Conclusions: A retrievable Rescue stent achieved rapid percutaneous hemorrhage control after a significant traumatic injury of the vena cava and allowed successful recovery of all injured animals. Further development of this approach may have utility in preoperative damage control of caval injuries.

Clinical Relevance: Noncompressible traumatic hemorrhage from injuries of the cava continues to have a high mortality, largely due to the inability to mitigate hemorrhage before arrival to the operating room. Current preoperative open and endovascular options for damage control present logistical challenges. A retrievable stent would offer a means to deliver hemorrhage control with continued venous return to the heart and yet without the limitations of current permanent stent designs. This study demonstrates a retrievable stent design for damage control of hemorrhage after caval injury in a porcine model.

Keywords

Retrievable; Stent; Hemorrhage; Cava; Porcine

Traumatic hemorrhage from the vena cava represents a challenging surgical dilemma with a significant mortality rate between 31% and 58%.¹⁻⁴ This may result from penetrating or blunt trauma or, alternatively, occur as an iatrogenic injury. The noncompressible nature of caval injuries presents additional challenges, as external manual compression is ineffective to mitigate ongoing blood loss. Aside from the obvious hemodynamic effects of hemorrhage, early blood loss exacerbates coagulopathy and increases the risks for other complications, such as long-term organ failure, even despite eventual replacement of lost blood volume.⁵ As a result, early hemorrhage control is critical for optimal surgical outcome.

Current approaches to caval injury present several obstacles to temporizing hemorrhage, especially outside of the operating room. Open clamp control of a caval injury is not well suited for the trauma bay or battlefield hospital, limited by brisk nonpulsatile caval bleeding, absence of qualified surgical staff, and compromised sterility. Endovascular options also present logistical challenges as “permanent” stent grafts require endovascular expertise, trained staff, properly sized inventory, and high-resolution imaging. Optimal initial placement of current stent grafts is essential as current permanent stents cannot be easily removed if they are improperly selected or placed.

A retrievable stent graft would resolve many of these challenges because hemorrhage control could be achieved rapidly in a damage control scenario. We have previously described “proof of concept” for a novel “petal and stem” stent design that allows rapid deployment and eventual recapture. Limitations of that study included a large 16F device profile, a terminal porcine model, and the use of open femoral and iliac vein exposure.⁶ This study included two primary objectives. The first was the development of a refined caval Rescue stent that includes percutaneous delivery of a more practical 9F stent profile. The second goal was to examine the refined stent in a more rigorous porcine survival model of caval hemorrhage and resuscitation, with successful postoperative recovery.

METHODS

Finite element analysis.

Finite element analysis was used to examine strain during stent collapse into a 9F sheath using Abaqus CAE 2016 software (Dassault Systemes, Waltham, Mass). A cylindrical surface model was included in the calculation process as a crimper to compress the stent radially. It was meshed with 1750 SFM3D4R (four-node quadrilateral surface element with reduced integration) elements. The nitinol behavior was simplified as elastic with Young modulus $E = 70$ GPa and Poisson ratio $\nu = 0.3$.⁷ Superelasticity was not included to simplify modeling complexity. The stent model was meshed with 14,594 C3D8R (eight-node linear brick with reduced integration and hourglass control) elements for the first design and 20,980 C3D8R elements for the second design. The mesh quality was checked to avoid any element distortions. The contact between the crimper (cylindrical surface model) and the stent outer surface was defined as frictionless in the tangential direction and “hard” contact (penetration not allowed) in the normal direction. Also, the separation was allowed after the contact, suggesting that they were not bonded together during the collapse process. A displacement loading was applied on the crimper surface in the radial direction, and the magnitude was set as the compressed stent diameter being equal to a 9F profile. Finally, the calculation was performed using dynamic explicit to account for the large nonlinear deformation. Both the stress and maximal principal strain (MPS) fields were calculated to determine the device integrity in a 9F sheath. We assumed that the stent strut would be mechanically stable without fracture when it was collapsed into a 9F catheter if the calculated MPS did not exceed the fracture limit of the nitinol material at 12%.⁸

Custom nitinol retrievable Rescue stent scaffolds.

The nickel-titanium alloy nitinol was fashioned into a cylindrical design of 25 mm in diameter using 0.0155-inch-diameter nitinol wire (Confluent, Fremont, Calif) by methods described previously⁶ but with significant refinement. The wires were first bent 150 degrees to create permanent deformation of the wire onto an aluminum mandrel. Next, the contacting wires were joined by precision-pulsed, microlaser welding (LZR 100; Sunstone Engineering, Payson, Utah) at 20-mm spacing to create diamond-shaped openings in the stent. Thermal shape setting was achieved by heating the stent to 500°C (Lindberg/Blue M Moldatherm Box Furnace; Fisher Scientific, Pittsburgh, Pa) and allowed distribution of stress points caused during welding. Rapid cooling of the stent to 20°C in 10 seconds (quenching) restored superelastic properties to the nitinol backbone. Radial force was

measured using a mechanical test system (FMS-500, Starrett; OCS Technologies, Cleveland, Ohio).

Expanded polytetrafluoroethylene (ePTFE) sleeves.

ePTFE was manufactured by Zeus Industrial Products (Orangeburg, SC) with a nominal inner diameter of 0.394 ± 0.03 inch and wall thickness of 0.005 ± 0.004 inch (127 μm). Because of manufacturing limitations of the vendor, the ePTFE was extruded at a diameter smaller than needed. A 28-mm angioplasty balloon (Z-Med; B. Braun, Bethlehem, Pa) was used to dilate the PTFE to the final application size of 23 mm. The final thickness of the dilated ePTFE averaged 60 μm . PTFE was adhered to the final stent scaffold using polyglycolic acid suture (Unify 7-0 suture; AD Surgical, Sunnyvale, Calif) and cyanoacrylate glue (Loctite 4902; Henkel Corporation, Westlake, Ohio). Initially, ePTFE was placed on the outside of the stent for the first four animals but was transitioned to inside the stent to reduce snagging during retrieval.

Venous hemorrhage model.

Seven Yorkshire pigs (79–86 kg; three males and four females) were placed under general endotracheal anesthesia as part of a University of Pittsburgh-approved Institutional Animal Care and Use Committee protocol. Sedation was maintained with a combination of inhaled isoflurane, ketamine (intramuscular), dexmedetomidine (intravenous), and propofol (intravenous). Prophylactic antibiotics included ceftiofur 5 mg/kg intravenously. Potentially fatal ventricular arrhythmias are common in the porcine model,⁹ and amiodarone 10 mg/kg intravenously was given preoperatively to reduce this occurrence.

A right jugular vein access was achieved percutaneously under ultrasound guidance, and an arterial line was placed in the left carotid by open surgical exposure. Abdominal exposure was obtained by a paramedian incision with exposure of the infrarenal vena cava. The animals were heparinized with 100 units/kg of heparin to simulate post-traumatic coagulopathy and as required by the porcine model because of rapid clotting of this model at baseline. Following 18-gauge needle access of the infrarenal vena cava, the Seldinger technique was used to injure the cava with a 22F dilator. The animals were intentionally hemorrhaged by 1200 mL, corresponding to class II hemorrhage, and the duration of hemorrhage was recorded. Blood was collected with a BRAT2 cell saver (Sorin Group, Arvada, Colo); red blood cells were centrifuged, washed, and placed into a bag as packed red blood cells (pRBCs) for reinfusion.

Postinjury hypotension was treated with normal saline, epinephrine, and phenylephrine until autologous pRBCs became available. The right femoral vein was accessed under ultrasound guidance, followed by placement of a long 9F sheath (45 cm long; Ocor, Palm Harbor, Fla) by the Seldinger technique. A 23-mm-diameter and 10-cm-long caval Rescue stent was delivered through the sheath and placed below the level of the renal veins under fluoroscopic guidance. Venography was then performed to document the vascular injury, stent control of the hemorrhage, and preserved flow beyond the stent. Temporary hemorrhage control with the Rescue stent was continued for a total of 1 hour. In the final step, the stent graft was retrieved by advancement of the vascular sheath over the fully deployed stent graft. This

collapsed the stent into the sheath. The cava was repaired with one of two methods, either 5–0 Prolene suture (Covidien, Minneapolis, Minn) or a custom 23-mm permanent stent made of nitinol and ePTFE (same design as the retrievable stent without the stem). The abdomen was closed with No. 1 polydioxanone (PDS) looped suture and interrupted nylon suture. On femoral sheath removal, compression was held for 10 minutes as the heparin was reversed with protamine. The right jugular introducer was exchanged for a 12F dual-lumen catheter (16 cm long) for continued postoperative venous access (Mahurkar Elite Acute Dual Lumen Catheter; Medtronic, Minneapolis, Minn). The left carotid was repaired primarily with 5–0 Prolene suture. Laboratory studies included complete blood count, chemistries, and arterial blood gases, which were drawn preoperatively, after hemorrhage, and then after resuscitation. Postoperatively, animals were recovered from anesthesia and received analgesics (buprenorphine 0.1 mg/kg or flunixin meglumine 2.2 mg/kg intramuscularly every 8–12 hours). Normal saline boluses were administered as needed for postoperative tachycardia. Laboratory samples were drawn at 24 and 48 hours postoperatively. Necropsy was performed at 48 hours to document any bleeding after repair. In addition to these animals, a single reference animal underwent 22F caval injury without stenting. Arterial blood pressure was recorded until the arterial transducer was no longer registering pressure readings. Thereafter, the time of cardiac arrest was determined by auscultation, followed by direct visual confirmation of the heart for absence of contractility.

Statistical analysis.

Data were examined using Stata 14 software (StataCorp LP, College Station, Tex). For each of the continuous, dependent variables (pH, lactate, hemoglobin, creatinine, transaminases, and mean arterial pressure), a repeated-measures analysis of variance was computed. Each analysis of variance was then followed by post hoc testing with Scheffe adjustment. Animals with incomplete laboratory data were excluded from analysis. Averages of physiologic, fluid, and laboratory values are shown with standard deviation.

RESULTS

An optimized scaffold offers improved mechanical and shape memory for a 9F delivery profile.

Critical to reduction of the delivery profile of a large 23-mm retrievable stent from 16F to 9F was preservation of structural integrity and shape memory properties when compressed into a 9F sheath. By finite element analysis, the strut junctions of the original stent⁶ demonstrated the highest stress concentrations, and the maximal stress value was 11,380 MPa. More important, the calculated MPS distribution revealed that the strain was 20.2%, which far exceeds the 12% fracture threshold for nitinol (Fig 1, A). In addition, the MPS exceeds the threshold for shape memory of nitinol. In total, this analysis predicted that if compressed into 9F sheath, the device would not deploy to its original shape and also carried a high probability for fracture. A second stent was designed to minimize strut junctions responsible for the high strain (Fig 1, B). The maximal stress value was reduced to 3470 MPa, and MPS value was reduced to 4.5%. This demonstrated that the refined stent design could be crimped into a 9F sheath while preserving shape memory and without structural failure of the nitinol.

A 9F profile venous Rescue stent demonstrates rapid deployment and retrieval.

A nitinol scaffold was fabricated with the new design and combined with a customized PTFE sleeve (Fig 2). Despite balloon dilation of the PTFE to the final size of 23 mm, the PTFE retained all expected fluid retention properties. To demonstrate that properties of stent deployment and recapture were preserved with scaffold modification, the refined stent was examined in vitro with a 9F sheath. Compared with a previous prototype 16F stent, the optimized Rescue stent was successfully loaded into a 9F sheath. As shown in Fig 3, the stent retained the ability for deployment by sheath withdrawal and retrieval by simple sheath advancement over the fixed stem to collapse the stent petals.

Uncontrolled caval hemorrhage in the porcine model.

One of the most notable aspects of noncompressible hemorrhage is the speed and magnitude of blood loss. Although the outcomes of caval injury are poor in humans, it was necessary to define the time course of uncontrolled caval hemorrhage specifically in the porcine model. A reference pig under general anesthesia underwent injury of the inferior vena cava with a 22F sheath with recording of arterial blood pressure over time (Fig 4). The representative time course is shown with cessation of cardiac activity within 8 minutes and 55 seconds of the injury and after 2175 mL of total blood loss.

Caval hemorrhage model simulates noncompressible hemorrhage.

The majority of caval injury patients will have sustained significant blood loss before presentation at a medical facility. As a simulation of the hemodynamic effects of blood loss, our porcine model included a standardized injury of the infrarenal cava with a 22F dilator and intentional class II hemorrhage. Heparin was administered to simulate the associated coagulopathy of massive hemorrhage and was also obligatory in the thrombosis-prone porcine model. Average time for the intentional and passive 1200-mL blood loss was <3.3 minutes. Beyond this initial hemorrhage, animals lost an average of 748 mL (± 508 mL) of blood during the remainder of the procedure. As there was no significant blood loss during Rescue stent placement, this additional loss was related to blood loss incurred during venographic imaging of the injury as well as at the time of permanent caval repair.

The average volume of pRBCs returned to the animal was 1079 mL. Despite prompt resuscitation with crystalloid (average, 3.2 L) and return of autologous cell saver blood, animals demonstrated both acidosis and elevated lactate levels as expected from massive acute blood loss. The average pH of each animal decreased significantly from 7.48 to 7.27 after resuscitation ($P < .001$). Lactate levels rose significantly from baseline (average, 1.8 ± 0.52) to midinjury (average, 4.5 ± 1.76 ; $P < .001$).

The venous Rescue stent achieves rapid hemorrhage control in vivo.

Following injury of the infrarenal vena cava and intentional class II hemorrhage, the venous Rescue stent was rapidly deployed under fluoroscopic guidance in <1 minute after femoral vein access. Hemorrhage control is illustrated from the perspective of the operative field (Fig 5) including the 22F caval injury, active hemorrhage, and stent coverage of the injury. In addition, hemostasis was documented angiographically (Fig 6). Angiography further confirmed continuous venous return through the stent toward the heart.

As illustrated in Fig 7, caval injury resulted in immediate hypotension with a fall in mean arterial pressure averaging 30 mm Hg ($P < .01$). Within minutes of stent placement, mean arterial pressure improved and revealed no significant difference from baseline among the seven injured animals. As a result of species-specific challenges for urinary catheters in the pig model (corkscrew phallus in male pigs), urine output was not recorded.

Animals demonstrate full recovery after caval injury and repair.

The Rescue stent was retrieved by simple advancement of the outer sheath, which reliably collapsed the stent for removal. During the brief interval between Rescue stent removal and permanent repair, sponge sticks were used for caval compression and hemostasis. There were no issues with the permanent repair of the cava. After definitive repair of the caval injury, removal of the 9F delivery sheath demonstrated successful hemostasis with 10 minutes of groin compression in all animals. Animals were then recovered and received an average postoperative normal saline bolus of 907 ± 1030 mL as needed for tachycardia. One animal developed a severe bradyarrhythmia during recovery from anesthesia that required atropine. This same animal was subsequently removed from the study at 24 hours as a result of a recurrent life-threatening bradyarrhythmia. Importantly, at necropsy for this animal, there was no evidence of hemorrhage. All other animals returned to normal ambulation and diet by postoperative day 1 and survived to the expected 48-hour end point.

Despite significant hemorrhagic shock, laboratory values at 24 hours were not significantly different from baseline for alanine transaminase ($P = .17$), aspartate transaminase ($P = .18$), or lactate ($P = .98$). In addition, transaminase, total bilirubin, hemoglobin, and creatinine values were all nonsignificant compared with preoperative baseline values among the six surviving animals at 48 hours.

DISCUSSION

Massive hemorrhage resulting from injuries of the vena cava remains a challenge for the operating room, much less the austere environment of a trauma bay or battlefield. Novel approaches to mitigate hemorrhage are likely to reduce complications associated with massive transfusion, iatrogenic injury during caval exposure, and delays in the treatment of associated traumatic injuries. Despite the grave urgency of these injuries, the noncompressible nature of caval injuries is prohibitive to effective preoperative hemorrhage control. This is compounded by logistical hurdles to open clamping or even permanent stents before arrival of a patient to an operating room.

Although balloon occlusion has gained popularity for hemorrhage control after exsanguinating aortic and pelvic trauma,^{10,11} application of balloon occlusion to caval trauma presents several potential disadvantages. Although use of a balloon for mitigation of caval hemorrhage has been examined in a porcine model,¹² the impact on cardiac physiology was not evaluated in that terminal study. It is likely that balloon occlusion of the cava would threaten crucial venous return to the heart, and if placed directly over the injury, an occlusive balloon could enlarge the existing injury of the thin-walled cava. Moreover, if placed proximal or distal to the injury, an occlusive balloon would allow continued distal or proximal backbleeding, respectively. As a result, control of caval backbleeding would

require a two-balloon approach.¹³ By contrast, a retrievable stent could achieve complete hemorrhage control without obstructing venous return and yet allow removal for repositioning or at the time of permanent repair. A prototype of such a retrievable stent was previously described and offered rapid hemorrhage control.⁶ Limitations of that study included a terminal porcine model as well as a large-profile prototype stent and requirement for open surgical vascular access.

In this study, the caval Rescue stent has been examined using a refined low-profile stent graft and a more comprehensive survival model of exsanguinating hemorrhage. This study was designed to simulate the hemodynamics of caval hemorrhage, to demonstrate damage control with a caval Rescue stent, and to conclude with definitive repair, resuscitation, and recovery. As a key advancement from the original prototype, the delivery profile of the Rescue stent graft was reduced from 16F to 9F. This smaller profile may offer improved hemostasis after sheath removal but also reduce thrombotic risk compared with an occlusive larger profile device, especially during prolonged damage control. The previous electrospun poly(ester urethane) urea sleeve has also been replaced by the more clinically familiar ePTFE. Despite a marked reduction in the delivery size, the stent graft still demonstrated both rapid deployment and retrieval.

The use of a 22F dilator corresponds to a caval injury size of 7.3 mm. Although the size of caval injury can certainly vary with mechanism, this size seems comparable to a significant caval injury, a conclusion supported by complete exsanguination of a control animal in <9 minutes. Class II hemorrhage before use of the Rescue stent was intended to simulate the hypotensive patient with noncompressible hemorrhage arriving to a trauma bay or battlefield hospital. This is important because many patients have sustained significant blood loss before arrival to a trauma bay. Use of heparin was required in the otherwise thrombogenic porcine model but also simulates the coagulopathy expected after major hemorrhage.

The choice of a 1-hour duration of the retrievable stent would seem to exceed the expected transport time of an average patient from a trauma bay to the operating room. This was done intentionally to demonstrate that the stent might be useful for extended periods. For instance, there may be additional delays resulting from associated injuries, prolonged operative exposure, transport of patients from a battlefield to a higher level hospital, or civilian mass casualty events when the volume of injured patients may overwhelm emergent surgical capacity.

Our model successfully demonstrated hypotension that was readily reversed with Rescue stent placement and traditional resuscitation. In the immediate postinjury period, animals experienced some expected postinjury acidosis and elevated lactate level as a result of the intentional blood loss before stent placement. Regardless, all of the animals were recovered and ambulatory by postoperative day 1 with normalization of laboratory values. Although one animal was removed from the study at 22 hours after injury, the precipitating event of a recurrent bradyarrhythmia was seemingly unrelated to the stent. Despite removal from the study, this animal had already demonstrated successful hemorrhage control by the stent and immediate postoperative recovery. These results of animals treated with the venous Rescue stent were in striking contrast to a reference animal that exsanguinated rapidly. The 9F

caliber of this approach is certainly comparable to venous introducers used clinically in humans and allowed hemostasis by manual compression without the need for open vascular repair or risk of thrombosis from venous stasis expected with a larger profile system. As illustrated in a previous study, the petal and stem, low radial force design of the Rescue stent is able to accommodate a wide range of vessel sizes, up to 30% smaller than the target size of the stent.⁶ This may potentially offer a single or few devices to accommodate a wide array of patients.

As a limitation of this study, fluoroscopic imaging was used for placement of the venous Rescue stent and may not be available in most emergency situations. Further experience will be required to determine whether anatomic landmarks, flat plate radiographs, or even newer technologies such as radiofrequency positioning⁶ will suffice for retrievable stent placement outside of an endosuite. Intravascular ultrasound, although it is a valuable tool in vascular interventions, may not be easily accessible within a trauma bay.

Another limitation of this study is the open abdomen component, which may not reflect the normal tamponade effect in a true penetrating trauma. The alternative of laparoscopy was not a feasible option for this model. The heavy bowel of the porcine model is not well suited for laparoscopic mobilization, and more important, there was a significant risk for fatal gas embolism during creation of such a large injury under pneumoperitoneum. Whereas the open abdomen model of caval injury lacked a tamponade element, it demonstrated the effectiveness of the stent, and the model was similar between our reference animal and the animals treated with the Rescue stent.

In this study, the infrarenal cava is indeed surgically approachable, and we did not investigate areas of more complex exposure, such as the iliac veins or the retrohepatic cava. It is noteworthy that in our previous study,⁶ we have demonstrated the ability of the Rescue stent to bridge between a smaller iliac vein and the larger cava with successful hemorrhage control. Use of the Rescue stent in the retrohepatic cava for the 1-hour duration of this study probably would not be tolerated because of hepatic congestion, but future studies may indicate whether brief use might mitigate hemorrhage during caval exposure in these difficult situations.

A stark reality of penetrating caval injuries is that many patients die in the prehospital phase, and significant hemorrhage may have happened even before arrival to a hospital. Although surviving caval patients who arrive to the emergency department are limited, the Rescue stent may have utility for iatrogenic injuries within the hospital as well, where the stent may allow time to collect expertise or equipment for a proper repair.

CONCLUSIONS

This study demonstrates that in a porcine model, a retrievable caval Rescue stent can effectively mediate damage control of caval hemorrhage using percutaneous access. In this model, early hemorrhage control translated to successful permanent repair and recovery after injury.

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ARTICLE HIGHLIGHTS

- **Type of Research:** Experimental study using a porcine model of traumatic caval hemorrhage
- **Take Home Message:** The authors found that a retrievable covered stent can control caval bleeding.
- **Recommendation:** This study suggests the potential utility of a retrievable covered stent technology for traumatic venous injury.

Fig 1.

Reducing the profile of a retrievable caval stent. **A**, Finite element analysis predicted that strain generated during compression of the original stent in a 9F sheath would exceed the thresholds for both mechanical failure and elastic shape memory for the stent. **B**, Revision of the stent to minimize wire connections reduced strain well under the memory and mechanical fracture thresholds.

Fig 2.

Refined 9F caval Rescue stent. **A**, Diagram of the caval Rescue stent with a sheath over the stem of the retrievable stent graft. **B**, Thermal shape setting of the revised nitinol scaffold on a mandrel. **C**, Final nitinol scaffold. **D**, Completed stent graft with a polytetrafluoroethylene (PTFE) sleeve.

Fig 3.
Rescue stent deployment and recapture. The venous stent constrained in a 9F sheath (**A**) and deployed (**B** and **C**). **D**, Recapture of the stent by sheath advancement.

Fig 4.

A time frame of uncontrolled caval hemorrhage in the porcine model. Following a caval injury at time 0, mean arterial pressure was recorded over time. Blood pressure was not measurable after 440 seconds (*open arrow*), and cardiac arrest was confirmed at 535 seconds after injury (*black arrow*).

Fig 5.

Caval hemorrhage control. Needle access (A) followed by a 22F dilator (B) resulted in venous hemorrhage (C), which is controlled with the venous Rescue stent (D) followed by rapid device retrieval after permanent injury repair. E, The retrieved stent is shown.

Fig 6.

Angiographic hemorrhage control. Compared with the uninjured cava (**A**), extravasation of contrast material (**B**, *dotted circle*) can be seen after 22F injury. The Rescue stent after placement (**C**) and hemorrhage control (**D**) was confirmed angiographically. *IVC*, Inferior vena cava.

Fig 7.

A Rescue stent improves hemodynamics after caval injury. Compared with baseline (–20 minutes), caval injury (–10 minutes) results in significant hypotension. Rapid normalization of mean arterial pressure occurs after placement of the Rescue stent (0 minutes).