Partial Resuscitative Endovascular Balloon Occlusion of the Aorta in Swine Model of Hemorrhagic Shock

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BACKGROUND: Complete resuscitative endovascular balloon occlusion of the aorta (C-REBOA) increases proximal mean arterial pressure (MAP) at the cost of distal organ ischemia, limiting the duration of intervention. We hypothesized that partial aortic occlusion (P-REBOA) would maintain a more physiologic proximal MAP and reduce distal tissue ischemia. We investigated the hemodynamic and physiologic effects of P-REBOA vs C-REBOA.

STUDY DESIGN: Fifteen swine were anesthetized, instrumented, splenectomized, and subjected to rapid 25% blood volume loss. They were randomized to C-REBOA, P-REBOA, or no intervention (controls). Partial REBOA was created by partially inflating an aortic balloon catheter to generate a 50% blood pressure gradient across the balloon. Hemodynamics were recorded and serum makers of ischemia and inflammation were measured. After 90 minutes of treatment, balloons were deflated to evaluate the immediate effects of reperfusion. End organs were histologically examined.

RESULTS: Complete REBOA produced supraphysiologic increases in proximal MAP after hemorrhage compared with more modest augmentation in the P-REBOA group ($p < 0.01$), with both groups significantly greater than controls ($p < 0.01$). Less rebound hypotension after balloon deflation was seen in the P-REBOA compared with C-REBOA groups. Complete REBOA resulted in higher serum lactate than both P-REBOA and controls ($p < 0.01$). Histology revealed early necrosis and disruption of duodenal mucosa in all C-REBOA animals, but none in P-REBOA animals.

CONCLUSIONS: In a porcine hemorrhagic shock model, P-REBOA resulted in more physiologically tolerable hemodynamic and ischemic changes compared with C-REBOA. Additional work is needed to determine whether the benefits associated with P-REBOA can both extend the duration of intervention and increase survival. (J Am Coll Surg 2016;223:359–368. Published by Elsevier Inc. on behalf of the American College of Surgeons. This is an open access article under the CC BY-NC-ND license [http://creativecommons.org/licenses/by-nc-nd/4.0/].)

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Disclaimer: The animals involved in this study were procured, maintained, and used in accordance with the Laboratory Animal Welfare Act of 1966, as amended, and NIH 80-23, Guide for the Care and Use of Laboratory Animals, National Research Council. The views expressed in this material are those of the authors, and do not reflect the official policy or position of the US Government, the Department of Defense, the Department of the Air Force, or the University of California Davis. The work reported herein was performed under United States Air Force Surgeon General approved Clinical Investigation No. FDG20140038A.

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Abbreviations and Acronyms

C-REBOA = complete resuscitative endovascular balloon occlusion of the aorta
IL = interleukin
MAP = mean arterial pressure
P-REBOA = partial resuscitative endovascular balloon occlusion of the aorta
REBOA = resuscitative endovascular balloon occlusion of the aorta

Hemorrhage is one of the leading causes of death in civilian and military trauma,[1-3] and mortality increases 7% for every 15 minutes that passes without definitive hemorrhage control.[4] However, transport times to reach trauma facilities frequently exceed 1 hour, and combat scenarios can require prolonged periods of prehospital field care.[5]

Resuscitative endovascular balloon occlusion of the aorta (REBOA) has emerged as a less invasive alternative to resuscitative thoracotomy with aortic cross-clamping for the treatment of patients in extremis from noncompressible hemorrhage. The less invasive nature of this catheter-based approach, coupled with the ability to proactively use this intervention before hemodynamic collapse, has resulted in a survival benefit over open aortic cross-clamping in early translational research and clinical experience.[6,7] Although in the United States REBOA is used primarily in fully resourced Level I trauma centers, this technique has the potential to be adapted for use in more-austere environments and for longer periods of time.[8]

Yet, the advantage of earlier intervention with REBOA is limited by the consequences of prolonged aortic occlusion.[9-12] Although REBOA can confer a short-term survival advantage by preventing exsanguination and augmenting perfusion of the heart, lungs, and brain, it is also associated with substantial morbidity from ischemia distal to the balloon.[7,13] Periods of occlusion exceeding 40 minutes can result in irreversible organ injury and death.[9-11] Additionally, supraphysiologic increases in blood pressure proximal to the occlusion balloon during complete REBOA (C-REBOA) can contribute to cardiac failure and exacerbation of traumatic brain injury.[14-17]

The morbidity associated with C-REBOA has led to the search for alternate endovascular approaches that still achieve effective hemorrhage control and mitigate the adverse effects of proximal hypertension and distal ischemia.[18] Intermittent balloon deflation regimens to perfuse distal tissue beds and limit ischemia have offered little benefit over C-REBOA in animal models and in clinical practice.[9,12] An alternative to this binary approach to aortic blood flow (ie complete occlusion alternating with no occlusion) is continuous, low-volume, distal perfusion achieved through partial aortic occlusion. This approach, termed *partial REBOA* (P-REBOA), is based on a previously described neurointerventional radiology technique of using partially occlusive balloon catheters to augment cerebral perfusion in stroke patients, and has only recently been attempted in the presence of noncompressible torso hemorrhage.[19-24] The physiologic impact of P-REBOA for sustained therapy in hemorrhagic shock has not been fully characterized. In an effort to test this effect, we hypothesized P-REBOA would preserve proximal aortic mean arterial pressure (MAP) closer to normal physiologic levels and concurrently reduce distal ischemia and systemic metabolic injury compared with C-REBOA in a porcine hemorrhagic shock model.

METHODS

Overview

This study was approved by the Institutional Animal Care and Use Committee at David Grant USAF Medical Center, Travis Air Force Base, Fairfield, CA. All animal care and use was in strict compliance with the *Guide for the Care and Use of Laboratory Animals* in a facility accredited by the Association for the Assessment and Accreditation of Laboratory Animal Care International. Healthy adult, castrate male and nonpregnant female Yorkshire-cross swine (*Sus scrofa*) obtained from the University of California, Davis, were acclimated for a minimum of 7 days. At the time of experimentation, animals were between 5 and 7 months of age, with a mean weight of 102 kg (±5 kg).

Animal preparation

Animals were premedicated with 6.6 mg/kg tiletamine/zolazepam (Telazol; Fort Dodge Animal Health) intramuscularly. After isoflurane induction and endotracheal intubation, maintenance anesthesia consisted of 2% isoflurane in 100% oxygen. Animals were mechanically ventilated with tidal volumes of 7 to 10 mL/kg and a respiratory rate of 10 to 15 breaths per minute sufficient to maintain end tidal CO_2 at 40 ± 5 mmHg. The pigs were placed on a warming blanket set at 39°C to maintain body temperature.

Both carotid arteries were exposed through a midline neck incision, and the femoral arteries were accessed through separate oblique groin incisions. Arterial access was obtained for controlled hemorrhage, hemodynamic monitoring, and to facilitate endovascular intervention.