REVIEW ARTICLE

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The Physiologic Perspective in Fluid Management in Vascular Anesthesiology

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INTRAVENOUS FLUID THERAPY, especially the crystalloid versus colloid debate, remains controversial in critical care medicine and anesthesia practice.[1–3] In contrast to studies on fluid regimens in septic patients or post-traumatic hemorrhagic shock patients, data from anesthesia and, particularly, vascular anesthesiology, are sparse. In addition, fraud in the scientific anesthetic community led to a retraction of several published manuscripts dealing with fluid management in the perioperative setting.[4]

However, not only which fluid should be preferred but also how it should be given are under intense discussion. Studies in major abdominal surgery raised concerns that generous fluid therapy may lead to fluid overload with consequent tissue edema formation, wound healing impairments, and more complications.[5] Since all these conflicting studies are published, practitioners should aim for a more rational approach to fluid therapy during anesthesia. Particularly in the vascular surgery patient with disturbances in the arterial vascular bed concomitant with impairment of tissue perfusion and the intraoperative ischemia-reperfusion syndrome, a deliberate amount and type of fluid therapy are of outmost interest for the anesthesiologist.

Vascular surgery involves different types of surgery and patients in different parts of the disease spectrum of vascular alterations. The focus of the present manuscript is to highlight the physiologic and pathophysiologic alterations of fluid administration in general, and especially in vascular surgery patients.

There is a lack of studies in this special surgical field, making a recommendation of how much and which fluid should be given in this special type of surgery very difficult. The present review tries to offer a different approach to the questions on amount and type of fluid that should be administered during vascular anesthesia. The focal point of this overview is placed on basic science and pathophysiologic changes during surgery and fluid replacement, followed with an overview of clinical data to give support in the decision-making of a rational approach for fluid replacement.

VASCULAR ALTERATIONS IN VASCULAR SURGERY PATIENTS

The endothelium is part of the barrier between the intraluminal vascular space and the interstitial tissue. In addition, the endothelium is a paracrine organ, and endothelium-derived vasoactive factors regulate vascular muscle tone and proliferation, inflammation, thrombosis, and fibrinolysis.[6] The endothelial cells, the endothelial basement membrane, the extracellular matrix, and the glycocalix all contribute to the endothelial barrier function that is modified by organ-specific gaps and fenestrations in the endothelial and subendothelial structures.[7] The glycocalix is a layer of membrane-bound proteoglycans and glycoproteins covering the endothelial cells on their luminal side.[8] The effect of fluid administration on global hemodynamics and on the local tissue mainly is influenced by endothelial function, the glycocalix being the key structure.[7] In vascular patients, the endothelium is hampered by arteriosclerosis and by local and global ischemia and reperfusion events.

Arteriosclerosis goes along with vascular (arterial) stiffness and intimal and medial calcification. Atherosclerosis is characterized by the growth of plaques that, after reaching a certain dimension, causes luminal stenosis. Fibrous caps cover the luminal side of the plaques. In plaques prone to rupture (vulnerable plaques), the fibrous cap gets thin. Rupture of the cap causes thrombus formation and complete (or subtotal) occlusion of the vessel.

Atherosclerosis is caused by, and causes further, endothelial dysfunction.[9] Ischemia and reperfusion damage endothelial cells and the endothelial glycocalix.[10] Ischemia and reperfusion occur repeatedly in patients with vascular disease, eg, during ischemic episodes in patients with peripheral arterial occlusive disease. In addition, all arterial vascular procedures are accompanied by temporal occlusion of an arterial vessel and consecutive reopening causing ischemia and reperfusion in minor or major parts of the body. These effects are most pronounced after temporary occlusion of the lower thoracic aorta with consecutive ischemia of the gastrointestinal system, the kidneys, and the lower part of the body. Ischemia and reperfusion phenomena not only alter local endothelial function, but also have general effects on the whole vascular system. Albuminuria occurring after exercise in patients with intermittent claudication and after infrarenal clamping for abdominal aortic repair gives evidence for changes in

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endothelial function in the kidney caused by ischemia-reperfusion injury outside the renal vascular system.[11,12] On the other side, compromised vasomotor and endothelial cell activation in patients with atherosclerosis may trigger ischemic events.[13] In addition, alterations in the structure of the glycocalix derange its effect on inhibition of coagulation and leucocyte adhesion.[14]

FLUID SHIFTS

Protein and fluid exchange from the intravascular space to the extravascular fluid compartment is a continuous process. This process is called the "transcapillary escape rate", which can be observed across the capillary membranes and the postcapillary venules.[15] Several characteristics of these microvessels make them favorable for fluid and solute exchange. One reason is the relatively slow blood flow in a vast surface area for exchange. Furthermore, capillaries and postcapillary venules are more permeable to solutes than in arterioles due to a decreased electrical resistance across the endothelial barrier.[16] An important characteristic of capillaries and postcapillary venules is the ability to alter their permeability to water and solutes in response to pathophysiologic conditions like inflammation.[17]

Fluid homeostasis is maintained via the Starling's equilibrium via hydrostatic and colloid oncotic pressures. The hydrostatic pressure in the capillary system minus the hydrostatic pressure in the interstitium pulls the fluid out of the capillaries. In the classic Starling model, this net pressure is counteracted by the oncotic pressure of the blood minus the oncotic pressure of the interstitial fluid pulling the fluid in the capillaries back. Only a small proportion of fluid returns to the circulation via the lymphatic system. Apparently, this classic model does not reflect the actual extracellular volume distribution expected after intravenous fluid administration.[7,18] Microvascular absorption in most tissues is transient, leading to a low rate of filtration and lymph formation. The lymphatics return to the circulation via the thoracic duct. This can be explained by standing plasma protein gradients across the intercellular cleft of capillaries, the so-called glycocalyx model.[18] For a broad overview and illustration of the revised Starling equation incorporating the glycocalyx model, see the review by Woodcock and Levick.[7,18]

Electrolytes and water can move freely between the intravascular space and the interstitium. This physiologic principle distributes isotonic crystalloid fluids over the whole extracellular compartment.[19] In healthy volunteers, infusion of 1 liter of 0.9% saline led to an escape rate of 68% from the intravascular space to the extravascular compartment.[20] In contrast, infusion of the same amount of 4% succinylated gelatine and 6% hydroxyethyl starch caused an escape rate of 21% and 16%, respectively, after end of infusion.[20] Similar findings of volume distribution after fluid resuscitation with either crystalloid or colloidal fluid were found in experimental hemorrhagic shock in animals.[21] In a porcine shock model with a calculated withdrawal of 50% of calculated blood volume, animals resuscitated with crystalloids required more than 3 times more volume than animals treated with colloids, indicating an almost unrestricted passage of crystalloids into the interstitial space.[21] As a result of this unlimited movement of water and electrolytes, the so-called Starling forces establish a new pressure balance across the capillary and postcapillary venule wall. The interstitial hydrostatic pressure increases by fluid accumulation, and the increasing dilution lowers interstitial oncotic pressure to a greater extent than intravascular oncotic pressure. Furthermore, compensation for increased fluid filtration by lymphatic drainage is insufficient in soft tissues.[22]

Recent data in intensive care patients suggest that during resuscitation, the ratio of crystalloid to colloid may be closer to 1.5 to 1 rather than originally thought to be on the order of 3 or 4 to 1.[23] Irrespective of the actual ratio, in the clinical setting colloid fluid therapy is associated with substantially less total volume of fluid administered.

The endothelial cell glycocalyx contributes to a selective barrier to movement of macromolecules from plasma to the endothelial surface.[14,24] Especially in patients with vascular disease, the glycocalyx may be damaged, contributing to an increase in endothelial vulnerability upon ischemia/reperfusion and hypoxia.[25,26] However, even more important in vascular surgery patients, ischemia/reperfusion injury by itself causes damage of the glycocalix of the endothelial cell, promoting an increase in permeability.[27] The damage of the permeability barrier allows macromolecules to cross from the intravascular space in the interstitial fluid, increasing the oncotic pressure in the interstitium with the consequence of edema formation.[28]

VOLUME EFFECT

The ideal resuscitation fluid in vascular surgery should have an immediate effect on intravascular filling already at small volume, remain intravascular in spite of an altered endothelial and glycocalix structure in the postischemic circulation, and exhibit antioxidant properties. Under physiologic conditions, albumin has a high anti-oxitative capacity and is the main protein building the intravascular oncotic pressure.[7] To generate this oncotic pressure, an intact endothelial glycocalix is mandatory where the albumin molecules adhere to the proteoglycans and glycoproteins of the endothelial glycocalix. Unfortunately, ischemia reperfusion destroys a substantial part of the glycocalix and disintegrates adherent junctions between endothelial cells, resulting in the well-known edema after reperfusion of ischemic tissues.[29] Because large plasma proteins like albumin and, to a lesser extent, the large molecules of artificial colloidal fluids cannot cross easily through the capillary walls, they mainly are responsible for the pressure generation. Synthetic colloids theoretically seem appropriate to compensate for a disordered endovascular barrier function, although their oncotic interaction with the glycocalyx is not as favorable as with albumin. However, animal models of acute inflammation and reperfusion showed that volume resuscitation by hydroxyethyl starch (HES) 130/04 prevented the extravasation of albumin to the interstitial space compared with crystalloids, leading to less tissue edema.[30,31] This short-term effect, unfortunately, disagrees with the clinical experience in which the requirements of colloids and crystalloids are quite similar.[32] In the last large randomized studies using HES in critically ill patients or septic shock, the ratio of crystalloid-to-colloid infusions was 1.3-1.5 to 1, a value far from the formerly