Perfusion assessment during cardiopulmonary bypass can be stratified into global and regional categories. This discussion will cover global assessment and selected regional assessments. Ingoing assumptions for this discussion are:

1. Heart and lung perfusion are “out of the loop” during CPB
2. The oxygenator is delivering adequate O₂ and removing adequate CO₂
3. Hemoglobin concentration is sufficient to support adequate global oxygen delivery throughout CPB.

The discussion will not address alpha-stat vs pH-stat management per se, but will assume alpha-stat management and systemic temperatures above 30 °C.

**Global Perfusion**

At its most fundamental level, perfusion during CPB gets down to pressures and flows. General management of flows and pressures were recently reviewed by Davis et al. (Davis 2008). If both are adequate, total perfusion is likely adequate unless there are extenuating circumstances such as hyperthermia, inadequate anesthesia or muscle relaxation, profound anemia, or a “zebra” such malignant hyperthermia or thyroid storm. All things being equal, total flows equivalent to what one would consider a normal cardiac index before or after CPB should suffice during CPB, e.g., a flow index of 2.2 L/min/m². In the presence of systemic hypothermia, the “target” flow can be reduced in proportion to the hypothermia by something along the lines of 5-10% per degree centigrade. This is an exponential reduction based on the flow level reached at any particular temperature, hence one would not reach any temperature at which zero flow could be sustained indefinitely. At a “drift” hypothermia level of 33 °C, one might reasonably assume that a perfusion flow index 20% below that required during normothermia is adequate, i.e., a flow index of approximately 1.8 L/min/m².

The optimal mean arterial pressure (MAP) range during CPB remains unclear after nearly six decades of clinical experience. Only one clinical study has randomly allocated patients to different pressure management strategies with constant flows (Gold 1995). That study suggested that MAPs in the range of 80 mmHg could reduce a “lumped” outcome including cardiac and neurologic complications. However, the separation of MAPs in the two study groups was less than intended, and the actual MAP achieved in the “high pressure” group was just below 70 mmHg. A follow-up study using the same data set suggested that patients with severe aortic arteriosclerosis benefited most from higher MAPs. In general, one cannot assume that any particular pressure management strategy is ideal for any particular patient, but the following strategy appears reasonable in the context of available data and common sense:

1. Sustained MAPs below 50 mmHg are not recommended, regardless of flow.
2. For some patients, MAPs above 60 mmHg appear appropriate. Risk factors for this need include severe aortic atherosclerosis; atherosclerotic narrowing of the arteries supplying major organs such as the brain, kidneys, and gut; advanced age (defined as > 70 years old?); and poorly controlled hypertension. It is possible that some patients with these risk factors would benefit from MAPs above 70 mmHg, but it is quite challenging to sustain such pressures in the presence of the hemodilution typically present during CPB.

Monitoring of systemic perfusion. Other than flows and pressures, the best global indexes of perfusion adequacy probably include arterial blood gases and mixed venous oxygen saturation. For arterial blood gases, one could assume that a progressive metabolic acidosis (especially if known to be a lactic acidosis) reflects inadequate global oxygen delivery unless proven otherwise. Similarly, in the face of adequate arterial PO2 and Hgb concentration, an SVO2 below 70% suggests inadequate perfusion flow (or possibly inadequate anesthesia).

Regional Perfusion
Discussion will be limited to the brain and splanchnic vascular beds. Cerebral perfusion assessment will primarily address cerebral oximetry. Although there are studies using other modalities, cerebral oximetry offers the most easily applicable technology other than depth of anesthesia monitors such as the BIS, which do not appear to be sensitive to cerebral ischemia.

Cerebral Perfusion. The need for a CNS monitoring technique that could reduce the incidence of perioperative stroke and neurocognitive dysfunction has been ongoing for decades. The incidence of stroke after cardiac surgery ranges from 1% to over 10%, and the incidence is influenced by such factors as increasing patient age, open vs closed cardiac surgery, preexisting aortic atherosclerosis, pre-existing cerebrovascular disease, and duration of cardiopulmonary bypass (Tan 2008). Both strokes and neurocognitive deficits after cardiac surgery substantially correlate with embolic phenomena that occur as a result of events surrounding CPB, but global hypoperfusion can also contribute to these deficits (Tan 2008).

If a cerebral monitor could serve as an early warning device and then alter patient management in a way that would reduce perioperative neurologic and neurocognitive deficits, this would constitute a major advance, especially in view of an increasingly elderly cardiac surgical patient population. Transcutaneous cerebral oximetry has been advanced as a means to that end. A number of case reports have cited regional cerebral oxygen saturation (rSO2) measurements as an early warning system for catastrophic events that were thought to have been avoided as a result of the measurements obtained (Tan 2008). Transcutaneous near-infrared oximetry (NIRS) utilizes many of the same two-wavelength near-infrared spectroscopic principles as pulse oximetry, but differs by being based on nonpulsatile reflectance spectroscopy that uses a mathematical algorithm to approximate a 75% venous/25% arterial oximetry mixture. Therefore, the most commonly used device (INVOS, Somanetics Corp., Troy, MI) approximates jugular bulb oxygen saturation by performing transcutaneous measurements from the forehead overlying the frontotemporal cerebral cortex. A similar device called NIRO is manufactured in
Japan (Hamamatsu Photonics) and lacks FDA approval to my knowledge. Relatively recently a transcutaneous cerebral oximeter called FORE-SIGHT (CAS Medical Systems, Inc., Branford, CT) has received FDA approval. This device purports to non-invasively measure and report brain tissue oxygen saturation every two seconds via near-infrared sensors placed on the forehead. Whereas interpatient variation in the baseline values obtained by the INVOS causes its manufacturer to strongly recommend a baseline determination prior to anesthesia and surgery, the FORE-SIGHT manufacturer believes that its determination of absolute brain oxygen saturation reduces or eliminates this need. Both devices provide bilateral frontotemporal information.

In a preliminary study, intraoperative FORE-SIGHT mean values in 32 CABG patients varied from 60% (CPB) to 72% (pre-CPB) (MacLeod 2006). Subsequent comments will be limited to the INVOS, the device on which most clinical reports about cerebral oximetry have been based. INVOS rSO2 readings may be adversely affected by the overlying skull and bone, by abnormal hemoglobins (i.e., methemoglobin and carboxyhemoglobin), by dyes such as methylene blue, and by high bilirubin levels (Tan 2008). At times unexplained asymmetry may occur in healthy patients (Tan 2008). As noted above, interpatient variability has confounded attempts to define a normal range, and a 20% decrease from baseline values has been defined as a likely threshold for concern and intervention. Recommended interventions have included increasing CPB blood flows, increasing blood pressure, increasing hemoglobin, adjusting cannula positions, deepening anesthesia, increasing PaO2, initiating pulsatile perfusion, and increasing PaCO2 (Tan 2008). 

Two observational or retrospective studies suggested that optimization of rSO2 during cardiac surgery reduced neuropsychologic deficits or strokes (Yao 2004, Goldman 2004). Hong et al. prospectively correlated rSO2 declines with postoperative cognitive dysfunction in 100 patients undergoing valve surgery (Hong 2008). They found no correlation between rSO2 and cognitive dysfunction, but patients with greater cerebral desaturation did require longer hospital stays. Murkin et al. performed a prospective, randomized study in 200 patients in which the control group had blinded rSO2 measurements and no interventions. Control patients experienced longer periods of rSO2 desaturation, longer ICU stays, and greater overall major organ morbidity and mortality (Murkin 2007). The outcomes of mortality, stroke, renal failure requiring dialysis, prolonged ventilation, deep sternal infection, and re-operation were combined to reach statistical significance. The Murkin study was elegantly performed, but the lumping of outcomes does raise some concern. One wonders if similar improvements might have been achieved by simply setting aggressive systemic perfusion targets involving flows, arterial pressures, and mixed venous O2 saturation levels. Operations involving particular risk to global or regional cerebral perfusion (e.g., circulatory arrest, selective antegrade cerebral perfusion, retrograde cerebral perfusion) have been advanced as particularly appealing situations for the use of cerebral oximetry. Accordingly, Kussman et al. recently monitored rSO2 during CPB in 104 infants undergoing biventricular repairs requiring CPB, 39 of whom required deep hypothermic circulatory arrest (Kussman 2009). They found no correlation between rSO2 and early postoperative outcomes after adjustment for
**diagnosis.** There was some variation in rSO₂ with anatomic diagnosis, however. Some authors advocate multimodal CNS monitoring during cardiac surgery, combining usual global perfusion markers with various combinations of cerebral oximetry, transcutaneous Doppler, and multilead EEG monitoring. These approaches have not as yet been subjected to prospective evaluation (Lozano 2004). The pros and cons of cerebral oximetry have been reviewed relatively recently, and few prospective investigations appear to be ongoing. Nevertheless, the various manufacturers of cerebral oximeters have mounted a marketing blitz targeted at cardiothoracic surgeons and anesthesiologists. The manufacturers appear to astutely recognize that some cardiac surgeons can be convinced to advocate for any monitor that might improve patient outcomes, even if the data supporting any single cerebral monitor or combination of cerebral monitors during cardiac surgery remains sparse. The expense of NIRS is not prohibitive, but neither is it negligible at $150-250 per case depending upon the device and upon the particulars of a contract.

*Summary:* Although there is justifiable enthusiasm for a monitoring technique that can diagnose cerebral insults in time to permit meaningful preventive intervention during cardiac surgery, the outcomes-based evidence supporting cerebral oximetry or multimodal cerebral monitoring used for that purpose remains thin. Anecdotal reports and some clinical studies are encouraging, but more prospective studies are needed before routine use can be strongly recommended.

**Splanchnic Perfusion.**
The gut may hold the keys to the long-term survival of such insults as CPB and sepsis. Release of inflammatory cytokines and gut flora into the circulation during CPB may set the wheels in motion for multiorgan failure. Some efforts have been made to assess gut “performance” during CPB, and this section will briefly review knowledge to date. Unfortunately, knowledge of the intestinal response CPB remains decidedly superficial. Some reports have suggested inadequate perfusion of the gut during CPB, while others have suggested hyperperfusion (Swanson 2008). Specific markers for gastrointestinal (GI) perfusion during CPB have been very limited, and serious GI complications of CPB occur in 0.5-3% of cases, although the possibility of an unrecognized GI role in pulmonary or even cerebral or cardiac complications is not that far-fetched. Risk factors for GI complications include the usual suspects: prolonged CPB duration, low perioperative cardiac output, embolic events, and valve surgery (Swanson). The use of gastric tonometry, which measures PCO₂ and sometimes pH, showed some early promise, and an instrument known as the Tonocap was even developed and marketed, but it appears to have ceased production.

The idea behind gastric tonometry was similar to the use of end-tidal CO₂ as a marker for circulatory adequacy, i.e., higher gradients between arterial and gastric PCO₂ suggest inadequate blood flow (Rossi 2004). Uhlig et al. suggested gastric mucosal tonometry as a sensitive marker of hypovolemia during CPB (Uhlig 1998). Hamulu et al. showed a reduction in gastric pH (while systemic pH remained normal) during CPB that normalized shortly thereafter (Hamulu 1998). Rossi et al.
demonstrated a progressive increase in the gradient between arterial and gastric pH that peaked in the sixth postoperative hour (Rossi 2004), and this coincided with elevated plasma concentrations of Interleukin 6. Rosamel and colleagues associated gastric pCO2 (among other factors) with mortality in ventricular assist device bridge-to-transplant patients (Rosamel 2007).
At this point, it is safe to say that the splanchnic bed is involved in, and perhaps even a contributor to, adverse outcomes following CPB. Whether or not any specific monitors or interventions might attenuate this relationship remains unclear.

Global Perfusion

Cerebral Perfusion/Oximetry
Tan ST, Hong Kong Med J 2008;14:220-5
MacLeod D, Anesth Analg 2006;102:S162
Yao FS, J Cardiothorac Vasc Anes 2004;18:552-8
Goldman S, Heart Surg Forum 2004;7:E376-8
Hong SW, Eur J Cardio-thor Surg 2008;33:560-5
Murkin JM, Anesth Analg 2007;104:51-8
Yeh T, J Thorac Cardiovasc Surg 2003;126:589-91
Lozano S, J Cardiothorac Vasc Anes 2004;18:645-56

Splanchnic Perfusion