

The Future ICU

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The Future of Haemodynamic Monitoring:

From Planet Mars to Resource-Limited Countries

When envisioning the future of haemodynamic monitoring, we cannot limit the discussion to new sensors and computer innovations. We also need to consider the accessibility to scientific and technological progress, particularly in resource-limited countries where a large number of patients deserve more rational haemodynamic management.

that recent surveys and audits have shown that the adoption of existing haemodynamic monitoring techniques is far from optimal, and that one of the key reasons is economic. Therefore, when discussing the future of haemodynamic monitoring we also have to consider that more patients from more countries need to have access to scientific and technological progress. In the second part of the manuscript, we will discuss alternatives to premium haemodynamic solutions, and how they could help rationalise haemodynamic management in resource-limited hospitals and countries.

The Future of Haemodynamic Monitoring in a Perfect World With Unlimited Resources

Let us imagine that we are in 2040 visiting a brand-new hospital built for the first human colony on planet Mars. This hospital would have been developed by an international consortium with virtually unlimited resources and would integrate the most recent medical innovations available on Mother Earth. The ICU would be a very quiet place where alarms would have been excluded from patient rooms (why bother

patients with alarms?). Alarms would be seen or heard or felt (haptic signal) exclusively by caregivers at central monitoring stations, or on mobile or wrist devices. Patients would be continuously monitored with wearable sensors (aka electronic tattoos: [youtube.com/watch?v=4oeFBGFzcrq](https://www.youtube.com/watch?v=4oeFBGFzcrq)). Some of these tiny, flexible and non-invasive sensors would be able to *feel* our carotid or femoral pulse and record high quality central blood pressure waveforms, from which blood flow information (e.g. stroke volume and cardiac output) would be derived by smart pulse contour algorithms (Michard 2016). Specific sensors would continuously monitor tissue perfusion and oxygenation, when not directly mitochondrial oxygen consumption (Vincent et al. 2017). Other adhesive skin sensors or biostamps would enable measurement of lactates, electrolytes and metabolites in sweat or interstitial fluid (of course, by 2040, clinical studies would have clarified the meaning and kinetics of these measurements).

Many of the above-mentioned sensors would be part of ergonomic monitoring tools such as helmets, shirts, belts, bracelets, gloves or rings worn by patients

The growing number of publications regarding new biomaterials, non-invasive sensors and artificial intelligence hold promises for the future of haemodynamic monitoring. In the first part of this article, we will briefly describe innovations that may become available soon in high-income countries and flagship hospitals. It is worth noting

(Michard et al. 2017a). Data would be transmitted wirelessly to computers and artificial intelligence systems able to filter artefacts, fuse parameters together and predict most adverse events before they actually occur (Pinsky 2016; Michard and Teboul 2019). Decision support systems would constantly help clinicians to think proactively, to make the right therapeutic decisions and to minimise drug side effects (Michard 2013). The use of central venous catheters would belong to the past, as well as their associated thrombotic, haemorrhagic and infectious complications (Vincent et al. 2018). Blood samples would be very small (the size of a blood drop) to prevent iatrogenic anaemia. When needed, larger blood samples would be obtained by robots using infra-red transcutaneous illumination and colour Doppler guidance (veebot.com/solutions.html) to improve safety, efficiency and decrease nurse workload. Electrical impedance tomography (EIT), routinely used for visual and functional lung monitoring, could also be useful to monitor stroke volume, cardiac output and pulmonary artery pressures (Braun et al. 2018). All doctors would have an echo probe in their pocket to *augment* clinical examination (**Figure 1**). High-end echo machines would only be used from time to time for detailed examination and when precise measurements would be necessary. These measurements would be greatly facilitated by smart systems recognising heart structures and movements and helping clinicians to properly position the probe.

The Future of Haemodynamic Monitoring in Resource-Limited Countries

In many hospitals and in many countries, what we envisioned for the flagship hospital on Mars will never be implemented for several reasons that include lack of awareness, lack of training and of course lack of resources. However, hypovolaemic, septic and cardiogenic shocks will likely remain a reality for millions of patients and thousands

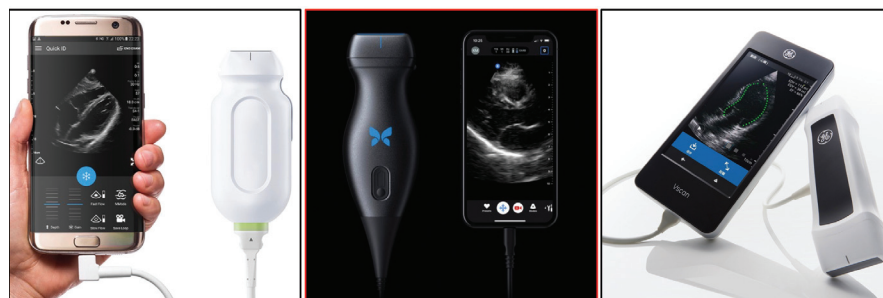


Figure 1. Examples of pocket echo devices. Given their relatively low cost, these devices have potential to be used not only in high-income but also in resource-limited countries. In a perfect world, most clinicians should have one in their pocket and be trained for basic qualitative ultrasound evaluations. From left to right: Lumify from Philips, IQ from Butterfly, VScan from GE Healthcare.

of caregivers working in resource-limited settings. In the following paragraphs, we describe existing and future solutions to improve the quality of care of patients with haemodynamic instability without necessarily increasing costs.

▲▲ upfront investment in monitoring techniques is often a barrier to hospital purchase and clinical adoption ▼▼

Predicting Fluid Responsiveness

Predicting fluid responsiveness is useful to rationalise fluid therapy. It helps to identify patients who may benefit from fluid administration and, perhaps more importantly, to prevent unjustified fluid administration in fluid non-responders. In emergency departments and intensive care units, the applicability of dynamic predictors of fluid responsiveness such as pulse pressure variation (PPV) is limited (Michard et al. 2015). Therefore, recommended methods to predict fluid responsiveness include the assessment of changes in stroke volume during a passive leg raising manoeuvre, an end-expiratory occlusion

test, a lung recruitment manoeuvre or simply during a fluid challenge (Michard and Biais 2019). The main limiting factor to the clinical adoption of these methods is the availability of a cardiac output monitor to quantify stroke volume changes. In this regard, several alternative methods have been proposed to predict fluid responsiveness (**Figure 2**). For instance, the decrease in PPV during a fluid challenge has proved to be proportional to the increase in cardiac output (Michard et al. 2000; Mallat et al. 2015). In other words, changes in PPV can be used as a surrogate for assessing changes in stroke volume or cardiac output during fluid administration. Similarly, the rise in PPV during a transient increase in tidal volume (e.g. from 6 to 8 ml/kg) has been shown to be useful to predict fluid responsiveness with high sensitivity and specificity (Myatra et al. 2017; Messina et al. 2019). Additionally, in patients who do not have an arterial catheter in place, pulse oximeters have recently been proposed to track changes in peripheral perfusion index (PI). Beurton et al. showed that changes in PI are proportional to changes in cardiac output during passive leg raising manoeuvres and able to predict fluid responsiveness with acceptable sensitivity and specificity (Beurton et al. 2019). De Courson et al. recently made the same observation during lung recruitment manoeuvres: most patients who experienced a dramatic decrease in PI during a recruitment manoeuvre were

fluid responders, whereas patients who did not, were fluid non-responders (De Courson et al. 2019).

Goal-Directed Fluid Therapy in High-Risk Surgical Patients

Most patients undergoing major surgery have an arterial line in place for continuous monitoring of blood pressure and blood samples. General anaesthesia with mechanical ventilation is also the rule in this context. In addition, atrial fibrillation, right ventricular failure, and decreased lung compliance are far less common in patients undergoing elective surgery than in critically ill patients. Protective mechanical ventilation is often described as a potential obstacle to the use of PPV. But it is only the case when very low tidal volumes are used (e.g. 6 ml/kg). If outcome clinical studies have shown that using a tidal volume of 6-8 ml/kg is better than of 10-12 ml/kg, until today there is no evidence than 6 is better than 8 ml/kg (Futier et al. 2013). Actually, a large observational study done in >29,000 patients from the UK suggested that the ideal tidal volume for surgical patients is around 8-9 ml/kg (Levin et al. 2014) and such a tidal volume is ideal to use PPV as a marker of fluid responsiveness. In summary, PPV can be used to rationalise fluid therapy in a large number of patients undergoing major surgery. Lopes et al. were the first to show a dramatic decrease in postoperative complications and hospital length of stay when using PPV to guide fluid therapy in a resource-limited setting (Lopes et al. 2007). Their pilot findings have been confirmed by several more recent clinical studies (Benes et al. 2014).

When cardiac output monitoring is a requirement to predict fluid responsiveness (e.g. when PPV cannot be used), recent studies have shown that pulse contour methods are the preferred choice of anaesthesiologists (Ahmad et al. 2015). However, despite the large number of stud-

PREMIUM SOLUTIONS	ALTERNATIVES
To assess cardiac function	To assess cardiac function
High-end echo evaluation (quantitative)	Pocket echo device (qualitative evaluation)
Continuous ScvO ₂ from fibre-optic CVC	On-demand ScvO ₂ from CVC blood sample
Advanced Swan + dedicated monitor	Basic Swan + regular bedside monitor
To track cardiac output changes	To track cardiac output changes
Pay-per-use pulse contour method	Pulse contour with unlimited usage plan
Pulse contour with disposable sensor	Disposable-free pulse contour system
To predict fluid responsiveness	To predict fluid responsiveness
SV changes during fluid challenge	PPV changes during fluid challenge
SV changes during EEOT	PPV changes during VT challenge
SV changes during PLR manoeuvre	PI changes during PLR maneuver
SV changes during lung recruit manoeuvre	PI changes during lung recruit manoeuvre

Figure 2. Haemodynamic monitoring solutions for resource-limited countries. Several monitoring solutions do exist to ensure that patients living in resource-limited countries may benefit from rational haemodynamic management. ScvO₂, central venous oxygen saturation; CVC, central venous catheter; EEOT, end-expiratory occlusion test; PLR, passive leg raising; PPV, pulse pressure variation; PI, peripheral perfusion index.

ies demonstrating the clinical value of pulse contour methods in surgical patients (Michard et al. 2017b), surveys and audits have shown that their adoption remains poor (Molliex et al. 2019). Most of these methods require the use of a disposable sensor, which is likely to double or triple the average cost of anaesthesia (around 100 euros in Europe). The onus of monitoring equipment has to be balanced with the potential savings related to the expected reduction in postoperative morbidity and length of stay. However, upfront investment in monitoring techniques is often a barrier to hospital purchase and clinical adoption. In addition, only a few hospitals have perioperative medicine departments and associated budgets. In most hospitals, anaesthesia departments have to pay for monitoring technologies used by anaesthesiologists, whereas the clinical benefits and associated savings are for the surgical departments. A solution may come from innovative business models recently proposed by several companies that, instead of charging for a single-use-sensor-per-patient, devel-

oped sensor-free pulse contour methods. The arterial pressure waveform is simply slaved from the bedside monitor towards a dedicated monitor or computer containing the pulse waveform analysis software. These companies usually charge hospitals a flat fee, that depends on the number of monitors they need, but not on the number of patients they treat. As a result, it gives clinicians the freedom to monitor as many patients as they want without increasing hospital costs (Figure 2).

In the future, one may also expect that bedside monitoring companies will develop or simply acquire existing pulse contour algorithms (Michard et al. 2019a). By doing so they will be able to offer cardiac output as a novel vital sign for all patients in whom a continuous BP waveform is recorded, either invasively from a radial catheter, or non-invasively from a volume clamp or tonometric sensor. Another option would be the improvement of methods based on the analysis of expired carbon dioxide (Peyton et al. 2019). These methods would have strong

potential for wide clinical adoption if they were integrated into anaesthesia machines.

Assessment of Cardiac Function

Echocardiography is gold standard for the bedside assessment of cardiac function in critically ill patients. Pocket echo probes are now available and have the potential to replace the stethoscope in the pocket of many clinicians, in the ICU and beyond (**Figure 1**). Although miniaturised, these tools have proven to be useful for a qualitative (e.g. pericardial effusion, right ventricular dilation, left ventricular dysfunction) or even quantitative assessment of cardiac function (e.g. estimation of left ventricular ejection fraction or inferior vena cava variations) (Biais et al. 2012, Liebo et al. 2011). Given their relatively low cost (as compared to high-end ultrasound machines), these pocket echo devices have the potential to be accessible to resource-limited countries and should help to increase the number of patients with shock who may benefit from quick ultrasound evaluations and rational haemodynamic management (Michard et al. 2019b).

Conclusion

Given the number of hardware and software innovations coming to market, the future of haemodynamic monitoring should be nothing but bright. However, the clinical adoption of existing solutions is somewhat concerning, with a minority of patients benefiting today from haemodynamic monitoring tools. In a medical world with increasing economic constraints, in parallel to the exciting development of technical and digital innovations, we must find ways to improve the accessibility of monitoring solutions to more patients and in more countries.

Disclosure

Frederic Michard (FM) is the founder and managing director of MiCo Sàrl, a

Swiss consulting firm. MiCo does not sell any medical device and FM does not own any shares from any medtech company. ■

Key Points

- Haemodynamic monitoring systems enable the rationalisation of haemodynamic therapy. Multiple studies have reported clinical benefits, particularly in patients undergoing high risk surgery.
- The clinical adoption of existing monitoring solutions remains low. The main barrier to wider adoption is the cost of single-use sensors.
- In many patients undergoing high-risk surgery under general anaesthesia, the conditions are met in order to use pulse pressure variation (PPV) to predict fluid responsiveness and rationalise fluid administration.
- In most patients, tracking changes in PPV can be used to detect changes in stroke volume and cardiac output during fluid challenges.
- Tracking changes in perfusion index (PI) may also have value to detect changes in stroke volume and cardiac output during passive leg raising and lung recruitment manoeuvres.
- The adoption of modern and affordable solutions for cardiac output monitoring should further help to ensure that more patients from more countries can benefit from rational haemodynamic management.

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