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Review Article

Digital innovations and emerging technologies for enhanced recovery programmes

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Abstract

Enhanced recovery programmes (ERPs) are increasingly used to improve post-surgical recovery. However, compliance to various components of ERPs—a key determinant of success—remains sub-optimal. Emerging technologies have the potential to help patients and caregivers to improve compliance with ERPs.

Preoperative physical condition, a major determinant of postoperative outcome, could be optimized with the use of text messages (SMS) or digital applications (Apps) designed to facilitate smoking cessation, modify physical activity, and better manage hypertension and diabetes. Several non-invasive haemodynamic monitoring techniques and decision support tools are now available to individualize perioperative fluid management, a key component of ERPs. Objective nociceptive assessment may help to rationalize the use of pain medications, including opioids. Wearable sensors designed to monitor cardio-respiratory function may help in the early detection of clinical deterioration during the postoperative recovery and to address 'failure to rescue'. Activity trackers may be useful to monitor early mobilization, another major element of ERPs. Finally, electronic checklists have been developed to ensure that none of the above-mentioned ERP elements is omitted during the surgical journey.

By optimizing compliance to the multiple components of ERPs, digital innovations, non-invasive techniques and wearable sensors have the potential to magnify the clinical and economic benefits of ERPs. Among the growing number of technical innovations, studies are needed to clarify which tools and solutions have real clinical value and are cost-effective.

Key words: enhanced recovery programme; digital innovation; wearable sensor

Since the initial description and implementation by Henrik Kehlet in 1997,[1] enhanced recovery programmes (ERPs) have been increasingly used to improve quality of surgical care across multiple specialties and countries. Although the name of such programmes may differ (ERAS for enhanced recovery after surgery, PSH for perioperative surgical home, ERIN for enhanced recovery in National Surgical Quality Improvement Program (NSQIP)), the process and goals are similar: establish a structure, organize and facilitate the integration of evidence-based components of care into practice over the entire duration of the surgical journey. Multiple studies have shown, and several meta-analyses have confirmed, the ability of ERPs to decrease postoperative complications and costs, and to shorten hospital length of stay.[2–4]

However, many clinicians have found the multifaceted and multiple elements of ERPs are difficult to implement and track.[5 6] In this regard, several studies have shown that compliance to ERPs is not always consistent, and that outcome benefits are directly proportional to the level of adherence.[7–9] Although leadership, motivation and coordination between stakeholders (surgeons, anaesthesiologists, nurse anaesthetists, nurses, physiotherapists, quality officers, etc.) play a major role in the successful implementation of ERPs,[10] emerging technologies can potentially help in many ways. The goal of the present narrative review is to describe and discuss the potential value of digital innovations, non-invasive technologies and wearable sensors to improve compliance to ERPs before, during and after surgery.

Smartphone applications (Apps) and text messages (SMS) for prehabilitation

The preoperative visit presents an opportunity to assess and optimize patient physiological condition before surgery, a major predictor of postoperative outcome.[11–13] Many Apps, downloaded on mobile phones or electronic tablets, may help prehabilitation by allowing improved management of risk factors.[14] Several of these Apps allow the connection between a smartphone and an electronic scale, a wireless blood pressure cuff, a glucometer, a wrist band or a watch equipped with accelerometers tracking physical activity. These Apps can be used to visualize trends over time, and thus provide an incentive for patients to maintain their weight, blood pressure and blood glucose within the normal range, as well as to increase their physical activity. Sending SMS to remind patients on preventative lifestyle and dietary measures has also been proposed to better manage the risk factors.[15] Systematic reviews and meta-analyses have confirmed that digital Apps and SMS may help to reduce body weight,[16] control hypertension,[17] improve glycaemic control,[18] increase physical activity[19] and for smoking cessation.[20] Because of frequent user dropout, the long-term effect of digital health interventions (Apps and SMS) has been questioned in the general population or in patients with chronic diseases.[14 15] However, this should be less of a problem over short periods of time before surgery. Finally, Apps and SMS could also be used to remind patients when to take or stop their medications, and may therefore have value to ensure patients adhere to preoperative recommendations.[21] Because digital interventions are inexpensive, studies are urgently needed to confirm their ability to facilitate and improve prehabilitation.

New tools for perioperative fluid management

Non-invasive haemodynamic monitoring: Fluid therapy is a key component of perioperative management and a key determinant of postoperative outcome.[22–24] A recent consensus article highlighted the risk of giving too little or too much fluid.[25] In high-risk clinical situations (e.g. estimated blood loss >500 ml, patients with co-morbidities) goal-directed fluid therapy (GDFT) has been proposed to tailor or individualize fluid management.[25 26] Studies have shown that GDFT protocols may decrease postoperative complications and hospital length of stay in various surgical populations.[27 28] Most GDFT protocols are based on flow parameters (stroke volume, cardiac output) or dynamic predictors of fluid responsiveness (pulse pressure variation, stroke volume variation). These haemodynamic parameters are usually measured by invasive haemodynamic monitoring techniques (thermodilution, invasive arterial pressure waveform analysis) or the oesophageal Doppler, a minimally invasive but operator-dependent method. Easy to use and non-invasive technologies have recently emerged[29] (Fig. 1). These new technologies include volume

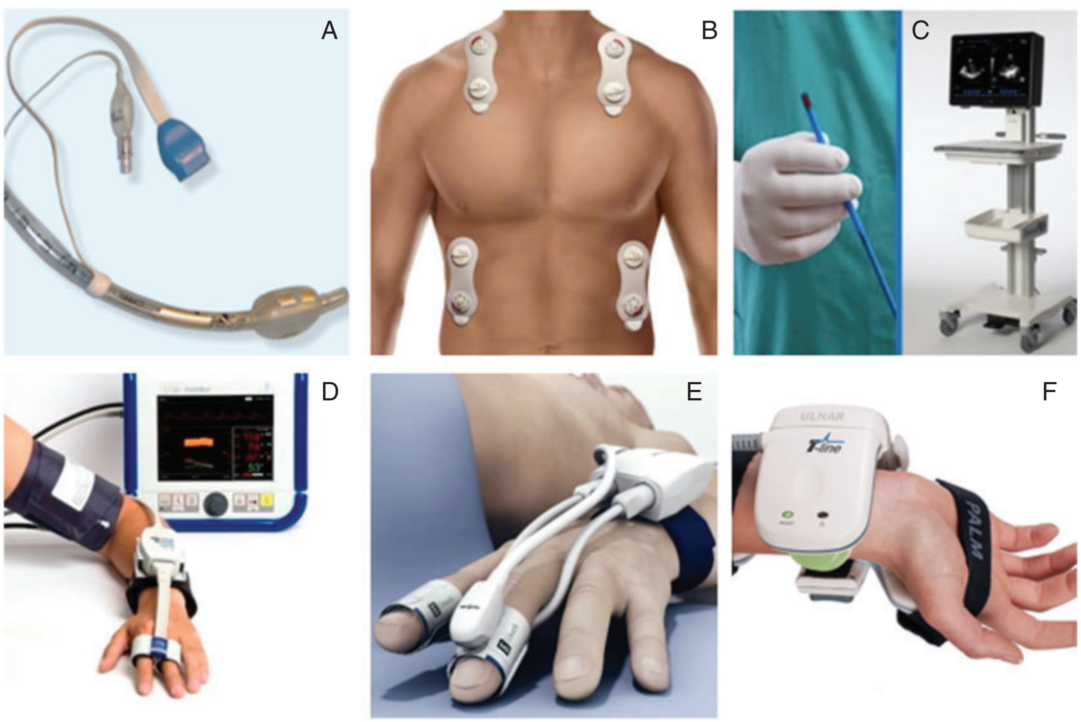

Fig 1 Examples of non-invasive haemodynamic monitoring techniques. (A) Bioimpedance tracheal tube (ECOM, San Juan Capistrano, CA, USA), (B) bioreactance electrodes (Cheetah, Newton Center, MA, USA), (C) miniaturized single-use transoesophageal echocardiography probe (Imacor, Garden City, NY, USA), (D, E) volume clamp finger cuff systems (CNSystems, Graz, Austria and Edwards, Irvine, CA, USA) and (F) applanation tonometry wrist device (Tensys, San Diego, CA, USA).

clamp methods and applanation tonometry for the continuous monitoring of blood pressure and advanced haemodynamic variables,[30] as well as bioimpedance tracheal tubes[31] and bioreactance surface electrodes[32] to monitor flow variables. Miniaturized and single-use transoesophageal echo probes are now available for visual monitoring of cardiac function and perioperative fluid needs.[33] In mechanically ventilated patients, the mere quantification of respiratory variations in the pulse oximetry waveform may also help to titrate fluid administration.[34] A few studies have already evaluated the effects of GDFT with non-invasive haemodynamic tools but failed to show any significant benefit on postoperative outcome.[35–37] However, some of these studies were underpowered, and little is known about the level of adherence to GDFT protocols. Therefore, more studies are needed to clarify the role of GDFT with new and non-invasive haemodynamic monitoring techniques in the context of ERPs.[38]

Decision support tools: Distraction and lack of tracking tools may explain why GDFT protocols are not always properly followed.[39 40] Visual displays—namely target screens—have been developed by several manufacturers to help clinicians achieving individualized haemodynamic targets (Fig. 2). These screens may be useful to improve adherence to GDFT protocols, but this remains to be proven.[41] Another option to improve adherence to protocols and decrease human factor variability is to use automatic or closed-loop fluid administration systems. Such devices are currently under development and have passed the feasibility phase.[42] Clinical studies are now needed to investigate their safety and their ability to achieve higher adherence rates than manual control by clinicians using visual decision support tools.

Emerging technologies for pain assessment

The optimal management of acute post-surgical pain is a key component of ERPs. Firstly, pain itself prolongs time to recovery milestones and delays discharge after surgery.[43] Secondly, opioids are still the mainstay of most postoperative analgesic regimens. While effective even for severe pain, their use prolongs length of stay due to dose-dependent side effects such as respiratory depression, sedation, postoperative nausea and vomiting, urinary retention and ileus.[44] Multimodal postoperative analgesia is defined as the use of more than one pain control modality to achieve effective analgesia while reducing opioid-related side effects.[45] Multimodal analgesia is a key element of ERPs but determining what are the optimal doses and combinations of pain medications remains a challenge. Several emerging technologies aim to quantify the degree of nociception using a variety of physiological variables. Heart rate and blood pressure changes, heart rate variability, pulse wave amplitude, skin conductance and electroencephalographic signals have been proposed for the objective assessment of pain.[46–48] However, they may lack of sensitivity or specificity when used individually.[49 50] It has therefore been suggested to combine several parameters to

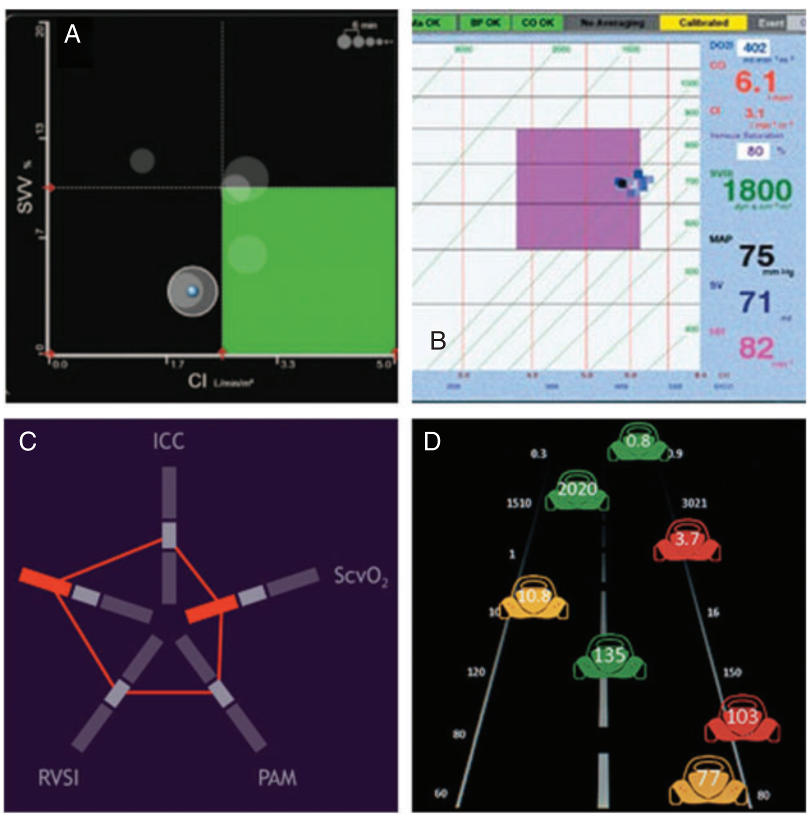

Fig 2 Examples of visual decision support tools. These screens are designed to help clinicians chasing haemodynamic targets in the context of individualized fluid management. Two dimensions (A from Edwards, Irvine, CA, USA and B from LiDCO, London, UK) and multidimensions (C from Pulsion, Munich, Germany and D from Tensys, San Diego, CA, USA) target screens.

better reflect the complex nature of pain.[50] The nociception level (NoL) index (Medasense, Ramat Gan, Israel) is a multidimensional index based on the non-linear combination of heart rate, heart rate variability, photoplethysmograph wave amplitude, skin conductance, skin conductance fluctuations and their time derivative, all obtained from a single finger sensor.[51] In 72 patients undergoing surgery, Martini and colleagues[51] showed that the NoL index outperforms heart rate and mean arterial pressure changes in differentiating noxious from non-noxious stimuli, and that under non-nociceptive conditions it is not influenced by opioid administration. Another recent study[52] showed during elective surgery that the NoL index responded progressively to increased noxious stimulus and discriminated noxious from non-noxious stimuli with a sensitivity of 87% and a specificity of 84%. Interestingly, the NoL index was also able to discriminate between two different opioid concentrations.[52] Studies are now needed to investigate how the objective assessment of pain impacts the use of pain medications, in particular of opioids, and whether it may help to enhance post-surgical recovery.

Tackling failure to rescue with innovative monitoring solutions

Postoperative complications are increasingly recognized as a major healthcare issue. The recent and large International Surgical Outcomes Study (ISOS) showed that 17% of patients undergoing inpatient surgery develop one or more complications.[53] The postoperative morbidity rate increased to 27% after major surgery, 30% in ASA III patients, 53% in ASA IV patients and 50% in patients who were admitted to a critical care unit as routine immediately after surgery. In addition, 2.8% of patients who developed a postoperative complication died before hospital discharge (failure to rescue). Postoperative mortality has been identified as the third leading cause of death in the USA, just behind heart diseases and cancer.[54] Importantly, many patients die in the wards, where the clinician/patient ratio is low and where patients are not continuously monitored.[53 55] Monitoring patients beyond the operating room and the intensive care unit (ICU) may allow the early detection of clinical deterioration and timely intervention.[56 57]

Despite the emergence of multimodal analgesia, opioid-induced respiratory depression remains responsible for some preventable deaths.[58 59] Several variables can be monitored to detect early respiratory depression and decrease the number of neurological sequelae or deaths. These variables include arterial oxygen saturation (with pulse oximeters), end tidal CO_2 (with capnographic sensors), respiratory sounds (with acoustic sensors) and minute ventilation (with thoracic impedance sensors) (Fig. 3). Taenzer and colleagues[60] implemented a monitoring system (Patient SafetyNet from Masimo, Irvine, CA, USA)

Fig 3 Examples of monitoring solutions to detect respiratory complications. (A) Contact-free piezo electric sensor (EarlySense, Ramat Gan, Israel), to be placed below the mattress, detecting the patient's heart rate (HR) and respiratory rate (RR). (B) Pulse oximeter (finger) and acoustic sensor (neck) to monitor HR, arterial oxygen saturation (Sp_{O_2}) and RR (Masimo, Irvine, CA, USA). (C) Capnographic sensor to monitor RR (Covidien, Boulder, CO, USA). (D) Impedance thoracic sensor to monitor RR, tidal volume and minute ventilation (Respiratory motion, Waltham, MA, USA).

based on pulse oximetry in over 2800 in-patients. The system was used to continuously monitor arterial oxygen saturation and heart rate, and alert nurses via wireless pager when physiological limits were violated. After the implementation of this system, they observed a 65% decrease in rescue events and a 48% decrease in ICU transfers. More studies are needed to confirm these findings and investigate the value of other monitoring methods.

Because they are 100% preventable, opioid-induced deaths have retained much attention over the last decade. But most common postoperative adverse events are infectious and cardiac complications.[53 61] Clinical deterioration in the wards may remain undetected for hours before clinicians are alerted and subsequently react.[62] A few studies have already suggested that combining respiratory and cardiac monitoring can potentially translate into a better postoperative outcome. In a multicentre international cohort study of >18 000 patients, Bellomo and colleagues[63] investigated the value of an advisory vital signs monitoring system (Intellivue MP5SC, Philips, Boebligen, Germany). The system automatically monitored patient temperature, blood pressure, heart rate and arterial oxygen saturation. These variables were used, in combination with respiratory rate and information on conscious state manually entered by the nurse, to calculate an early warning score used to alert caregivers in case of clinical deterioration. This new strategy, based on vital signs monitoring, was associated with improved survival after rapid response team treatment and with a decrease in median length of hospital stay. More recently, Brown and colleagues[64] used a contact-free sensor (EarlySense, Ramat Gan, Israel), placed under the mattress, to continuously monitor heart rate and respiratory rate in 2314 patients hospitalized in a medico-surgical unit. They observed a significant reduction in the rate of calls for cardiac arrest and in hospital length of stay when comparisons were made with a large historical group of patients or with a parallel control group who did not benefit from the new monitoring system.

The ongoing development of wireless and wearable sensors (Fig. 4) creates a unique opportunity to monitor the cardio-respiratory function of ambulatory patients in the hospital and beyond.[65] Non-invasive wireless and wearable sensors are now able to monitor physiological variables such as heart rate, heart rate variability, respiratory frequency, arterial oxygen saturation and thoracic fluid content.[65 66] Many of these tools have already received the Food and Drug Administration (FDA) clearance, but independent clinical studies are needed to confirm their accuracy and more importantly to demonstrate their clinical utility and cost-effectiveness in the post-surgical setting.[67] Once it becomes possible to monitor patients during the recovery period (i.e. when early mobilization is highly desirable), smart and robust software are needed to filter artifacts and prevent alarm fatigue.[68] Given the low clinician/patient ratio in surgical wards, various physiological signals and variables also need to be integrated (data fusion) into single warning scores or wellness indexes,[69–71] so that nurses can easily and accurately identify patients who are in the process of worsening condition (Fig. 5). Assuming technical and software challenges (data filtering,

Fig 4 Examples of wearable and wireless sensors. Medical grade adhesive patches (A from VitalConnect, San Jose, CA, USA, B from Isansys, Abingdon, UK, C from Sensium, Abingdon, UK and D from Intelesens, Belfast, Northern Ireland) and necklaces (E from CloudDX, Kitchener, Canada and F from toSense, San Diego, CA, USA) designed to monitor heart rate, respiratory rate, thoracic fluid content, temperature and/or activity in ambulatory patients.

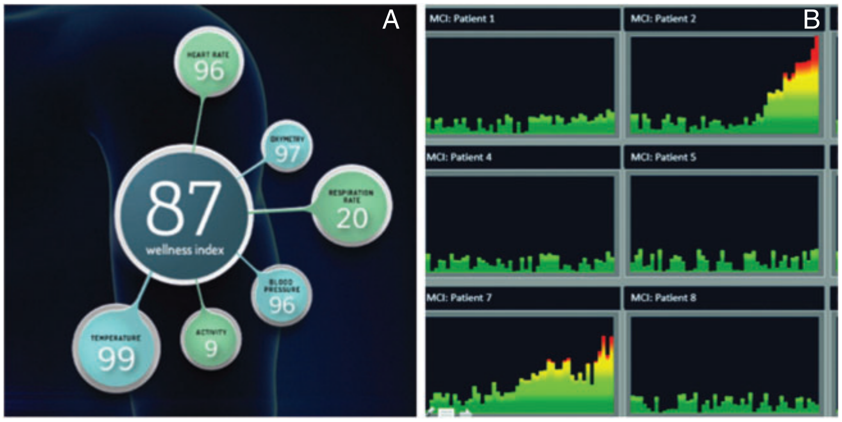

Fig 5 Example of data fusion system. (A) Several variables are integrated to create a single wellness index and (B) self-explanatory graphical display allowing the immediate and visual recognition of patients' deterioration by nurses working in the wards (PhysIQ, Naperville, IL, USA).

data fusion) can be overcome, remote and mobile monitoring may help tackle the clinical and economic burden of postoperative complications and preventable deaths in surgical wards.

Monitoring functional recovery with activity trackers

Postoperative recovery outcomes are usually assessed by procedure-specific quality of life scores with different patient-reported outcome measures (PROMs) and satisfaction scores. Their usefulness has been questioned because of their subjectivity.[72 73] Several studies have demonstrated a discrepancy between objective functional assessment and different PROMs.[74] Thus, activity levels do not always increase after total hip and knee arthroplasty[74] and objective functional assessments are desirable to better understand the underlying reasons.[75] Future efforts to optimize functional recovery should include objective assessment of function by actigraphy.[76–78] Activity trackers or wearable accelerometers are now ubiquitous. Several studies suggest that some consumer products, placed on the waist, upper arm or ankle, are accurate enough for the objective assessment of mobility.[77 78] However, caution should be exercised when monitoring slow walking speed populations,[79] which is often the case early after surgery. Future studies will need to investigate whether the use of these simple wearable and digital tools can help improve postoperative mobility.

Electronic checklists

Checklists have been shown to be useful to implement processes and improve quality of care.[80 81] Electronic checklists have been developed to ensure that none of the ERP elements is omitted during the surgical journey. Most of them are available as Apps and have been designed both for patients and caregivers, as well as to improve communication between the two. Although appealing, these tools remain to be evaluated in the context of ERPs before recommending their systematic use.

Conclusion

Emerging technologies have the potential, in or outside the context of ERPs, to help both patients and caregivers improve quality of surgical care. Prehabilitation could be facilitated by the use of SMS and Apps designed for smoking cessation, promoting physical activity and improving the control of hypertension and diabetes. Several non-invasive haemodynamic monitoring techniques and visual decision support tools are now available to facilitate the individualization of fluid management, a key component of ERPs. Sensors designed to monitor physiological variables should help for the early detection of postoperative clinical deterioration and to decrease preventable deaths. Activity trackers may be useful to monitor objectively early mobilization, a major postoperative element of ERPs. Finally, electronic checklists could be used to ensure that none of the ERP elements is omitted during the surgical journey.

By optimizing compliance to the multiple components of ERPs, digital innovations, non-invasive technologies and wearable sensors have therefore the potential to magnify the clinical and economic benefits of ERPs. Among the growing number of emerging technologies, studies are urgently needed to clarify which tools and solutions have real clinical value and should be implemented.

Authors' contribution

Contributed to the preparation of the manuscript and approved the final version: all authors.

Declaration of interest

F.M. has been a consultant to Pulsion Medical Systems, Dixtal, Hamilton Medical and UPMED, and an employee (VP, Global Medical Strategy) of Edwards Lifesciences. He is the founder and managing director of MiCo Sàrl, a Swiss consulting firm for medtech companies and digital health startups.

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