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Improving Fluid Management in Critical Care – Towards the ICU of the Future

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Abstract. Background: The calculation of daily fluid balances is essential in perioperative and postoperative fluid management in order to prevent severe hypervolemia or hypovolemia in critically ill patients. In this context, modern health information technology has the potential to reduce the workload for health care professionals by not only automating data collection but also providing appropriate decision support. Objectives: Within this work, current problems and barriers regarding fluid balancing in cardiac intensive care patients are outlined and improvement activities are specified. Methods: Literature research and qualitative interviews with health care professionals were conducted to assess the state-of-the-art technological setting within an intensive care unit. Results: An example case shows that interconnecting not only devices but also wards can facilitate daily clinical tasks. Conclusion: Smart devices and decision support systems can improve fluid management. Several technologies, which today are sometimes still considered to be futuristic, are in fact not that far away or already available. However, they need proper implementation with respect to intensivists', nurses' and patients' needs.

Keywords. Intensive Care, Information Technology, Clinical Decision Support

1. Introduction

As in other areas, modern technologies find more and more their way into healthcare and do not stop in front of hospitals. At the moment, also intensive care units (ICU) are on move to interconnected institutions, where the Internet of Things (IoT) plays an important role in meeting the steadily rising trend for personalization. However, despite all advantages of digitalization, also new challenges due to e.g. novel measurement methods or big data arise when modernizing an existing ICU by introducing smart devices and innovative sensors for a nearly continuous monitoring of vital parameters or biomarkers [1].

An area, where especially interconnection of devices could decrease the workload for health care professionals (HCP) and increased data quality could enhance treatment individualization, is intra- and postoperative fluid management. The administration of

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fluids in critically ill patients is widely discussed in terms of type, amount, timing and outcomes [2-7]. However, recent works indicate that in cardiac intensive care the amount of fluids rather than the type needs to be chosen with care and that the fluid balance – as a strong indicator for the current fluid therapy's efficacy – should closely be monitored [8]. The fluid balance is defined as the difference between all fluid intakes and all ongoing fluid losses [9]. Ideally, intakes and losses balance each other and the overall fluid balance is zero. In critically ill patients, fluid dysbalances should be avoided [10] and the presence of fluid overload might be an important clinical marker when estimating the risk for the development of an acute kidney injury (AKI) [11]. Within ICUs, setting targets for daily fluid balancing plays an important role in guiding removal of excess fluids [12]. In case of a severe fluid overload, under certain circumstances the use of renal replacement therapy may be preferable to the administration of diuretics [12].

For determining the fluid balance, administered fluids and ongoing losses have to be recorded accurately. A study by Bashir et al. [13] showed that in addition to the recorded fluids up to 1.5 liters of "hidden" fluids are administered to a patient each day. In contrast to healthy adults, patients might have additional sources of water and electrolyte losses resulting from e.g. bleedings or fever. In daily fluid balance calculation at the ICU, at least an insensible fluid loss of 10ml/kg/day should be considered in non-intubated patients [14]. During surgery, urinary fluid losses and losses through perspiration sum up to approximately 0.5-1.0 ml/kg/h [15].

The objective of this work is to outline current problems and barriers in fluid management, especially in fluid balancing of cardiac intensive care patients from a technological point of view. Furthermore, an improved setting within a cardiac ICU is sketched, which facilitates fluid management in critical care.

2. Methods

2.1. Knowledge base for developing an integrative ICU concept

Qualitative interviews with HCP (n=12) differing in years of experience were conducted in order to obtain detailed information on the typical settings and workflows in critical care. Discussions with nurses and physicians working in intensive care settings were initiated in order to identify current obstacles and generate ideas for improvement. A semi-structured literature research (keywords e.g. fluid management, fluid balance, intensive care, health information technology, decision support, automation, state of the art, trend, future) revealed how state-of-the-art as well as future technologies could contribute to a smart and more user-friendly environment.

2.2. Fluid management: Patient-specific parameters in a current intensive care setting

Patients staying at ICUs are typically surrounded by a range of medical devices, which are necessary for either monitoring the health status or delivering therapies. Figure 1 shows several devices, whose parameters and measurements need to be considered in fluid balancing. Depending on the type and severity of the disease, a large number of parameters are assessed either frequently or if necessary. Recorded data contain numerical values such as the amount of urinary excretion or ordinal-scaled values for defining severity levels and disease stages. An example for routinely used scales are the RIFLE and AKIN criteria for staging AKI [16].

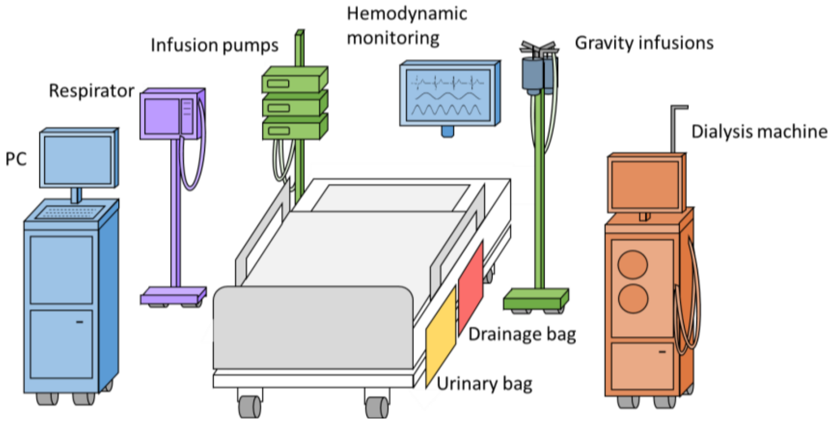

Figure 1. Devices important for fluid balancing stationed around a critical care patient's bed.

Hemodynamic vital parameters such as heart rate, blood pressure or ventilation as well as administered fluids and medications are recorded automatically and transmitted to a patient data management system (PDMS). Fluid losses are still entered manually using fill level readings on fluid containers. In general, the manual calculation of fluid balances is time-consuming but accurate documentation seems to be helpful in AKI prevention [17]. In catheterized patients, urinary losses are usually recorded several times a day, whereby an hourly monitoring is probably associated with less development of fluid overload and a better detection of AKI [18]. Fluid losses such as sweating or insensible losses via skin and lungs are often not taken into account. However, in case of high fever an additional fluid loss of approximately 500 ml/day can be assumed [14].

To our knowledge, the preoperative fluid balance of patients undergoing elective cardiac surgery is not assessed but might have an impact on intraoperative fluid management. The perioperative fluid balance is often not available in the ICU caregivers' PDMS due to a missing interface to the intraoperative documentation system. This leads to assuming neutral balances for patients arriving at ICU. Therefore, the initiated postoperative fluid therapy is not adequate because of a – sometimes – strongly under- or overestimated postsurgical fluid status [15]. In general, there seems to be a need for improving the transmission of intraoperative fluid management data from the operating room to the ICU at patient handover in terms of information quality and availability [19].

3. Results

The basis for an efficient fluid management in intensive care are availability, correctness, completeness and user-friendly display of relevant data. In order to achieve that, the following aspects should be considered when moving towards the next-generation ICU.

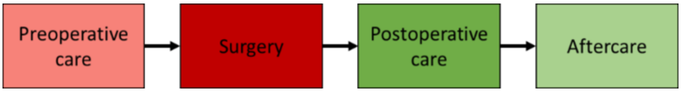

Figure 2. An elective cardiac patient's way through the hospital.

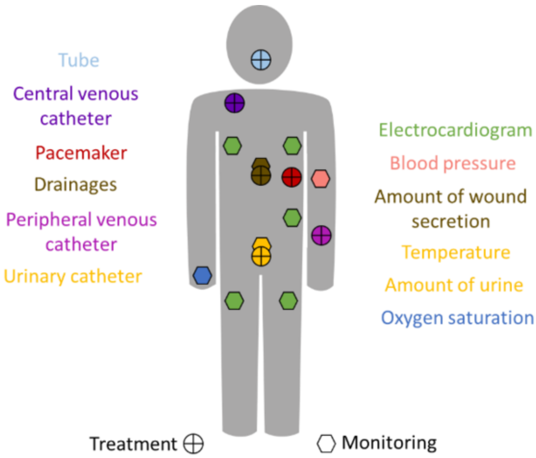

Figure 3. Common accesses and data capture sites in cardiac intensive care patients.

3.1. Closing interface gaps and establishing sensor networks

During an elective cardiac surgery patient's stay at the hospital, he or she passes several units (see Figure 2). It should be ensured, that all relevant information regarding the patient's stay at the current ward is available to the following one at patient handover at the latest.

Especially assistive or not routinely used devices around the patient bed such as extracorporeal membrane oxygenation (ECMO) or dialysis machines are often not connected to the PDMS and work as standalone systems where manual data transfer is needed. It is important to close these interface gaps to reduce workload for caregivers and to avoid errors due to manual data entry. Furthermore, the more data from different sources are integrated, e.g. preoperative baseline parameters or results from blood gas analyses, the better the basis for decision support systems (DSS) and algorithm-driven care [20] is. For instance, real-time data from continuous renal replacement therapy (CRRT) with interfaces to electronic health records (EHR) represent an important feedback loop for estimating the amount of medication filtered by the dialysis machines and could be used for an (semi-)automated adjustment of infusion rates [21].

Intensive care patients are usually equipped with a range of monitoring and treatment accesses, depending on the disease and the standard operating procedures of the respective hospital. Some of them are displayed in Figure 3.

Cable-bound sensors for monitoring purposes should be replaced by wireless solutions whenever their application makes sense and contributes to a more user-friendly environment [22]. Ad-hoc sensor networks should be established with respect to safety and security [23]. Figure 4 shows how intelligent sensor networks can build the basis for an individualized fluid management.

3.2. Introducing decision support systems but avoiding alarm fatigue and social silos

In critical care, HCP are faced with a range of measurements, displayed in form of either a current measurement value or time series. Simultaneous interpretation of up to 10 vital parameters is often necessary for assessing a patient's current condition [24]. Therefore,

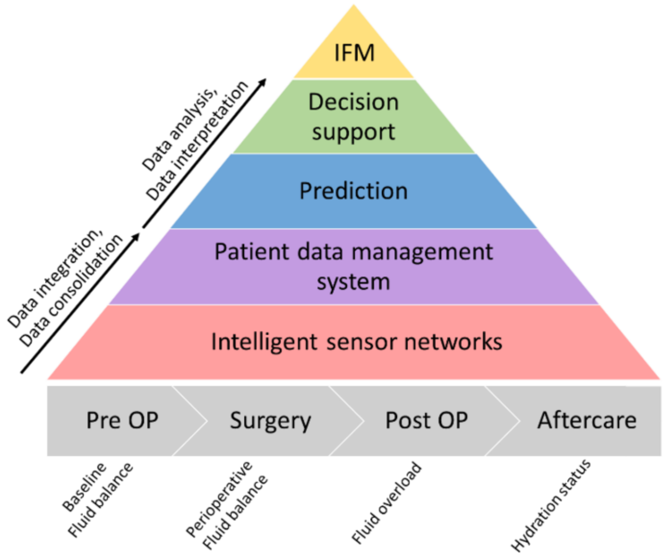

Figure 4. Intelligent sensor networks can build the basis for individualized fluid management (IFM) by enabling cross-departmental and user-friendly collection of vital parameter data.

it is important to reduce the amount of displayed parameters to the currently important ones. Clinical DSS based on machine learning algorithms might aid in selecting them and ensuring an intuitive and meaningful data representation. Additional parameters processed by background algorithms might be used for indicating changing health conditions and suggesting treatment options.

It is beyond debate, that acoustic alarm in case of worsening vital parameters is important. However, an appropriate and not too sensitive adjustment of the limit values for alarms leads to a reduction in physiologic monitor alarms [25] and therefore contributes to avoidance of alarm fatigue and facilitation of patient recovery [26-28]. Furthermore, alarm sounds should be melodic and easy to learn [29].

Comprehensive DSS are designed with respect to the actual user group, integrating all available data, providing prediction and giving assistance in planning next treatment steps. Nevertheless, cross-departmental communication among HCPs is essential and should be fostered to maintain treatment quality and avoid social silos [30].

3.3. The integrative ICU – an exemplary use case

John is 65 years old and has to undergo elective coronary artery bypass grafting (CABG). At the day of admission, besides several intake interviews with HCP and a baseline blood count, also a baseline fluid balance of -500 ml is determined using bioelectrical impedance analysis [31]. The obtained parameters are automatically transmitted to a central PDMS system. At the cardiac surgery unit, the integrated DSS suggests options for how to best reach a neutral fluid balance until surgery – which takes place the next morning – considering dinner, preoperative fasting and estimation of losses to be expected during night.

At surgery initiation, an algorithm estimates John’s fluid balance based on the administered fluids since admission, allowing the anesthetist to keep track of his actual fluid status. During surgery, important blood electrolytes such as sodium, potassium or chloride are permanently monitored using a wireless inline-measurement system reducing blood loss. Those measurements as well as the administered fluids and recorded losses are automatically stored in the surgery protocol within the PDMS. Fluid losses and gains through the heart-lung machine are taken into account as well.

After surgery, John is transferred to the cardiac ICU, where a bed has already been assigned to him automatically by the bed management system being part of the PDMS. Each bed is equipped with a tablet, which provides a clear overview of a selection of John's vital parameters. Besides the measurements from the inline system and hemodynamic parameters, an estimation of the postoperative fluid balance is displayed. John's postoperative values are in range, accept for a slight fluid overload of +700 ml. The flow rates of administered fluids and medications as well as those within drainages and the urinary bag are continuously measured and automatically updated in the PDMS.

In the evening, the urinary flow rate steadily decreases and the inline-measurement of potassium shows upward tendency. The DSS recommends the measurement of kidney-specific laboratory parameters and suggests first countermeasures. Since the parameters are not yet in a critical range, the responsible HCP are notified via smartphone and smartwatch messages. Compared to baseline measurements, John's vital parameters worsen during the next day. At the evening of the second postoperative day, his fluid balance increased to +4000 ml and the prediction algorithm shows a further upward trend. Since the intravascular volume is in range, the DSS indicates an increased risk for AKI and suggests the consultation of a nephrologist, which can directly be video-called or messaged using John's bedside tablet. Later in the course of his stay, a CRRT has to be started whereby the parameters of the dialysis machine are set using the values suggested by the DSS. All status variables of the dialysis machine are permanently monitored and wirelessly sent to the PDMS.

In the following days John recovers, the CRRT is terminated since diuresis and blood parameters normalized and the inline-electrolyte measurement system is removed. With a slightly positive balance of +200 ml, John is handed over to aftercare, where HCP already received a digital summary of John's stay.

4. Discussion

Mobile devices and apps are important tools not only for documenting and monitoring a patient's health status but also for consulting guidelines or obtaining decision support [32]. During perioperative care, DSS are already used for estimating e.g. complication risks or severity of illness [33]. In fluid management of the near future, introducing feedback loops using hemodynamic parameters will play an important role in prevention of hypo- and hypervolemia [34]. First approaches for guiding fluid therapy have already been published [35,36].

Some of the technologies described in the exemplary patient case are already available. For instance, the inline-measurement of blood components – which has the advantages of no blood loss and real-time data – is possible [37]. A sensor network dedicated to the use within critical care has already been developed by Shnayder et al. [23]. However, in the far future those networks might partly be replaced by all-in-one solutions [38]. Sensors themselves will reduce in size and be available in form of wearables [39]. Medical devices within the ICU might even be replaced by ingestible smart pills [40].

However, in fluid management integrative and patient-oriented systems based on our proposed concept will gain in importance. A first essential step in tackling current implementation barriers is the introduction of license-free and state-of-the-art interfaces enabling devices to transmit data to the PDMS. User-friendly sensing, automated and secure data capture, the introduction of intelligent and non-unobtrusive DSS but also the maintenance of face-to-face discussions and collaboration will be necessary to ensure an optimal monitoring of patients on their journey through the hospital.

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