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## Design and Evaluation of a Patient Monitoring Dashboard for Emergency Departments

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### Abstract

Identification of risk patients in emergency departments is a complex interplay between clinicians, patients, working procedures, and information systems. Through a mixed methods approach, we have developed a novel patient monitoring dashboard that couples clinical data streams to convey the state and trajectory of patients admitted to the emergency department. In this paper, we describe the design and implementation of the novel system by providing a description of how the project was conceived, divided into subsequent phases, and is currently being executed. Experience from this work highlights the importance of carefully assessing each on-site installation point, interdisciplinary partnerships through embedded presence, and continuous emphasis on the purpose and aim as a mean to greatly improve project momentum and buy-in.

### Keywords:

Emergency service, hospital; Decision support systems, clinical; Monitoring, physiologic

### Introduction

Identifying patients at risk of unforeseen deterioration in emergency departments (ED) remains an ongoing challenge despite numerous initiatives to formalize and systematize observations, tracking the state and trajectory of patients, and responding to changes to avoid complications.

In this paper, we provide a description of how this challenging clinical problem sparked a collaboration between engineers and clinicians resulting in the design, implementation, and evaluation of a novel patient monitoring dashboard. As we describe the prototype, process, and inter-disciplinary collaboration, we aim to provide a set of recommendations for similar attempts in assessing the impact of new health information systems. In doing so, we seek to extrapolate key findings that are decoupled from the initiating problem of detecting deterioration, and which instead point to more general challenges in systems design and implementation within secondary healthcare.

The inception of this project, originates from the work of Henriksen et al. who found that as many as one in three patients whose vital signs are within normality at admission, have an abnormal vital sign registration within the first 24 hours [1]. These patients have a higher risk of being transferred to the intensive care unit, experience heart or respiratory failure during admission, and a higher 7-day mortality. Identifying patients at risk in EDs spurred a research project collaboration between software engineers and

clinical researchers to leverage their joint knowledge for proposing a way to alleviate the risk of unforeseen deterioration.

### Related Work

A multitude of protocols and observation regimens have been introduced, evaluated, and often implemented in the last 20 years. Still, it is hard to come by evidence that undisputedly points to significant changes in patient outcomes due to the implementation of an Early Warning Score (or similar). The hospitals involved in this study relied on the DEPT triaging system for assessing the severity of patients [2]. DEPT deploys a mixture of objective (e.g., blood pressure) and subjective observations (e.g. pain), see Figure 1. The most severe observation determines the overall severity and priority of the patient.

	1 RED Life-threatening	2 ORANGE Urgent	3 YELLOW Less urgent	4 GREEN Not urgent	5 BLUE Fast track
A	Airways blocked Inspiratory stridor	Airways blocked Inspiratory stridor	Airways open	Airways open	Unaffected fast track patients will be by default not have their vital values measured.  If the condition of the patient change, the need to measure vital signs will be reassessed.
B	SpO <sub>2</sub> < 80% w.o. O <sub>2</sub> SpO <sub>2</sub> < 90% w. O <sub>2</sub> RF > 25 or RF < 8	SpO <sub>2</sub> < 80% w.o. O <sub>2</sub> SpO <sub>2</sub> < 90% w. O <sub>2</sub> RF > 25 or RF < 8	SpO <sub>2</sub> < 95% w.o. O <sub>2</sub> RF > 25	SpO <sub>2</sub> > 95% w.o. O <sub>2</sub> RF > 8 and RF < 25	
C	Pulse > 140 bpm SysBP < 80 mmHg	Pulse > 140 bpm SysBP < 80 mmHg	Pulse > 110 bpm or Pulse < 50 bpm SysBP > 90 mmHg	Pulse < 50 bpm or Pulse < 110 bpm SysBP > 90 mmHg	
D	GCS < 8	GCS < 14 or GCS > 8	GCS = 14	GCS = 15	
E	Temp < 32C	Temp < 32C	Temp > 38C or Temp < 35C	Temp < 38 C or Temp > 35C	
B	For COPD patients: SpO <sub>2</sub> threshold is lowered 5%				
	SpO <sub>2</sub> < 75% w.o. O <sub>2</sub> SpO <sub>2</sub> < 85% w. O <sub>2</sub>	SpO <sub>2</sub> < 75% w.o. O <sub>2</sub> SpO <sub>2</sub> < 85% w. O <sub>2</sub>	SpO <sub>2</sub> < 90% w.o. O <sub>2</sub>	SpO <sub>2</sub> > 90% w.o. O <sub>2</sub>	

Figure 1 - The DEPT Triage System

Part of the challenge relating to the utility of these systems, is not only due to the heterogeneity of patients, but also the variety in experience, background, and profession of attending clinicians [3]. Another major factor is the socio-technical complexities that come into play when mixing this variability with information technology.

Several sophisticated novelty detection systems have been proposed over the years. Clifton et al. published several studies on the application of Gaussian process regression for dealing with missing values and forecasting of trajectories [4], and also investigated extreme value theory as a mean to perform online learning of patient-specific models [5]. Clifton et al. are also one of the few groups that succeeded in advancing a system beyond the pilot evaluation stage, and actually tested their system in realistic settings [6]. Another substantial line of work originates from Edelson & Churpek who developed the CART score to predict cardiac arrest [7]. Perpendicular to the issue of modelling and prediction, we found a need to assess how to best visualize the system state.

Although there has been slow progress on systems designed for patients to monitor themselves, clinical dashboards and data aggregation have been subject to much work [8]. Generally, there seems to be less focus on taking a pragmatic stance to improve utilization and integration of existing streams of data, and integration of these into information systems in ways that improve the clinical perception of multiple patients simultaneously.

## Methods

As the project has been ongoing since early 2013, we have split the methodology description into several stages. First, an initial stage from 2013-2015 focused on early scoping that took place at the ED of Odense University Hospital, and resulted in a prototype of a patient monitoring dashboard. The second stage from 2016-2017, was the system prototype maturation and integration into additional information systems. The third stage ran from 2018-2019, and focused on a multidimensional effect evaluation.

From the very beginning of the project, it quickly became apparent that clinical epidemiologists and engineering researchers had substantially different approaches to designing and conducting research. As software engineers, we did not have any prior experience with the clinical, technical, and operational aspects of EDs. Consequently, we needed to design our study approach in a manner that embedded us within the context.

To achieve this, we designed the project using a mixed methods approach where we could explore several pathways to illuminate potential solutions to the problem of identifying patients at risk. This led us down three distinct paths as illustrated in Figure 2, each path highlights a number of related activities.

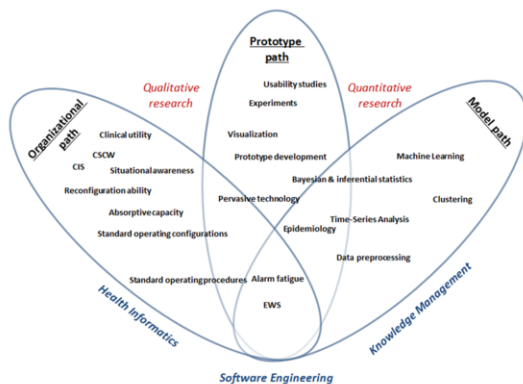


Figure 2 Methodological Project Paths

Firstly, as outsiders familiarizing ourselves with the context of our problem proved to be indispensable. To begin we mapped out an 'organizational path', which sought to clarify how clinicians dealt with the matter of patient processing, monitoring, and treatment. To do this, we deployed a number of tools, some were methodological by nature, and others were frameworks or research fields that helped us to understand the domain. The understanding of how clinicians worked with patients and the systems they utilized was then paired with data from actual patients. This data was the cornerstone of the 'modelling path', where we sought to understand patients and patient monitoring systems using a number of quantitative techniques, with the intention of deriving novel features and new ways of representing and understanding patients and monitoring systems. The 'organizational' and 'modelling' paths

came together in the 'prototype' path where we attempted to validate assumptions from both of these paths. This was achieved via different prototype modalities, supported by usability studies.

### Initial Stage – Early Scoping

Our first major effort was conducting a field study of the context. The first author of this paper followed physicians, nurses and nurse assistants on full work shifts at all times of the day and took note of how patients were attended to, how clinicians registered observations personally and collaboratively, and how information technology was used during the admission [9].

In parallel with this, we needed to establish a foundation for building better deterioration detection models with predictive analytic models. During the field study, we had observed several occasions where patients expressed individual normality that was not captured by the existing population-based threshold models. However, acquisition of vital signs from patients was not something the existing information communication (IT) configurations supported. Vital sign observations were registered in the department's electronic healthcare record according to protocol, but the registration frequency were low, and automated data extraction was not an option.

Coincidentally, a network diagram of the patient monitoring platform emerged while discussing other integration options with the local medical device engineers. This revealed that the ED had purchased a Philips IntelliVue™ solution that included a database server that automatically buffered all registrations from connected monitors. Thus enabling the HL7 Parameter Data Interface (PDI) allowed us to export vital sign readings at a configurable interval from the Philips database.

### The Data Collection

Each bed at the department was equipped with a Philips IntelliVue MP30/50™ monitor. Each monitor had a Philips X2 Measurement™ module, which could follow the patient during transfers. Each monitor had capacity to monitor heart and respiration rate through 3-lead electrocardiography, peripheral oxygen saturation (spO2) and pulse rate using pulse oximetry, and systolic/diastolic blood pressure (SBP/DBP) using non-invasive cuffs. To retrieve data we built a registration server that acquired registrations from all active monitors every minute using the HL7 PDI interface. The attending nurses were asked to register patients on the Philips monitors by name and social security number to enable later coupling with external health registries.

### Prototype Design

The final phases of the initial stage focused on distilling the findings from all activities into a prototype system of a patient monitoring dashboard. Through incremental collaboration with clinicians, a functional prototype was implemented and evaluated in a pilot study involving 18 nurses and 50 patients [10]. The participating nurses were also asked to assess the system using the System Usability Scale [11], and results indicated that the overall design philosophy of the system made it easy to understand and use.

### Second Stage - Refinement

After having successfully evaluated the prototype, we went on to acquire funding for further development of the system. This was achieved by funding from the Strategic Initiatives Program by the University of Southern Denmark through a 2M DKK grant. This gave us the opportunity to rewrite the entire prototype and explore new ways to deal with the

challenges of coupling registrations from the patient monitors with the department's clinical logistics system. The new system was dubbed the Patient Deterioration Warning System (PDWS). During this stage, the project grew in organizational complexity as an additional site was included, and the newly enforced General Data Protection Regulation had incentivized the IT departments across the region to impose stricter control with installation and evaluation of information technology for research purposes.

### Third Stage – Effect Evaluation

Having rewritten the entire PDWS system, and tested deployment and operational stability of the system, the third stage of the project focused on conducting an effect evaluation. The intention of this larger trial was threefold:

1. To assess if deploying the PDWS into EDs would help clinicians identify patients who deteriorated unexpectedly.
2. To investigate if the design philosophy of the PDWS fitted well within clinical work.
3. To evaluate if utilizing the PDWS could help the departments in improving efficiency and quality.

### Cluster Randomized Trial

The evaluation has been designed as a cluster randomized trial (CRT) consisting of three intervention and three control periods interleaved at each study site. Each period, lasting five weeks, has been separated by a one-week washout buffer. The study aims to include 10.500 patients, which will yield sufficiently material for evaluating the clinical hypothesis that the PDWS can reduce unexpected deterioration by 50%. The primary clinical outcome has been defined as patients who are transferred to the Intensive Care Unit, suffer from heart/respiratory failure, or die during admission. The evaluation stage will be assessed by journal review by clinical experts.

The CRT was initiated May 2018 and is scheduled to run until early 2019. During the period, project nurses and assistants will include patients at each site. Following the CRT period, data from all consenting patients will be transferred to a research repository and used for further research.

### Study Sites

The first part of the study (field study, initial vital sign registration, and prototype pilot evaluation) was conducted at the Emergency Department of Odense University Hospital (OUH). OUH has an uptake population of 430,000 citizens and its ED has an capacity of 44 beds. The second part of the study expanded the participating sites to include also the ED of Hospital of South Western Jutland (HSWJ). HSWJ has an uptake population of 220.000 citizens and its ED operate 51 beds.

Although both EDs are situated in the Region of Southern Denmark, and are part of the same healthcare system, each ED organizes the patient admissions very differently. For example, at the ED of HSWJ, a patient is usually never transferred internally once admitted. Whereas in OUH, patients are seen and treated in a short term Acute Treatment Center for the first eight hours of admission, and then later transferred to the Center for Accelerated Patient flows for the remaining part of their admission.

### Approvals

The project has been presented to the Scientific Ethics Committee of Southern Denmark, but does not need approval according to Danish legislation. The Danish Data Protection

agency has accepted that we store data (J. nr. 17 14630). Research data are managed by OPEN (<http://Open.rsyd.dk>). Data from patients who provide informed consent will be used for the effect evaluation stage, and for future work in predictive analysis.

## Results

As the project is still ongoing, and parts of it has already been described in other work, for the paper, we seek to draw out some of the lesser known aspects – while still combining the entirety of the project to convey the key lines of results.

### Data Acquisition

During the first part of the project, we acquired all registered vital signs over a two-year period as part of the initial prototype implementation. Although only a subset of these vital signs could be distinctly linked to specific admissions, the dataset in its entirety gave us a unique insight into the utilization of patient monitoring in the ED at Odense University Hospital. Table 1 lists the summary of all registrations. The number of registrations in relation to sensor type was evident, as we observed a decreasing number of registrations due to sensor nuisance.

Table 1- Vital Signs Registered During the Initial Stage

Vital Sign	#Registrations	Mean	Std.Dev
Heart rate	4,668,890	88 bpm	21 bpm
Respiration rate	4,491,545	20.4 rpm	5.7 rpm
Pulse rate	7,277,427	84.4 bpm	19.3 bpm
spO2	7,181,895	95%	3.8%
SBP	232,895	124 mmHg	26.4 mmHg
DBP	232,895	68.4 mmHg	17.9 mmHg

We evaluated the distributions of each vital sign type, and interestingly found distinct differences to what is considered normal vs. alarming thresholds according to the NEWS system [12]. Heart and pulse rate readings only exceeded the upper limit of 131 bpm in 3% of all cases, and just 0.2% of all readings were below 42 bpm. These numbers were much higher for respiration rate registrations where 16% surpass 25 rpm, and just 0.4% are lower than 8 rpm. 10% of spO2 registrations were lower than 91% oxygen saturation, and this was even without factoring in patients being administered additional oxygen. For systolic blood pressure, 7.5% of readings were lower than 90 mmHg which was quite substantial given the risk of low blood pressure [13].

### Deriving Novel Metrics for Monitoring

Another line of work attempted to identify different models of normality for a range of clinical and patient specific factors [14]. Although we did not find support for the presence of such normality ranges, we instead identified clusters of patients who generally had vital signs within non-alarming thresholds, but with a distinctly higher mortality ratio. The main difference to similar clusters was a higher standard deviation. Thus, we identified a group of patients who seldom triggered any alarms, but still expressed high variability. This led to the inclusion of the metric 'Relative severity', which was implemented as an aggregated sum of shifts between states. Clinician could thus order patients by highest severity as prescribed by the attending physician, or by variability.

The degree of monitoring a patient was exposed to during admission was formalized in both departments by observation regimens. For example, a patient who was classified as



Figure 3 The Patient Deterioration Warning System - Client System

Orange was to be continuously monitored, and have vital signs registered in their electronic health record hourly. However, from our exploratory analysis of the vital sign dataset, we found that several factors, both patient and department specific, influenced the extent to which patients were monitored [15]. The findings of this work were utilized in the PDWS, as abnormal device utilization could be used as a marker for clinical concern.

### The Patient Deterioration Warning System

The PDWS consists of a backend system implemented in Java™ using Spring v.4 with Hibernate for persistency and Envers for entity auditing, and a front-end implemented in AngularJs v.5. The PDWS interface is shown in Figure 3, and has been described in other work [10]. The system conveyed the state and trajectory of all admitted patients who at some point in time had been monitored using any of the department's vital sign monitors. All registered readings were scored using the DEPT system and aggregated into configurable periods of time with respect to the expected length of stay for a given ward. As the system automatically stored all vital signs from monitored patients every minute during their entire stay, and linked these with admission information, we were able to gradually establish a very detailed dataset of all patients admitted to the participating EDs.

The project as a whole made a giant leap forward when we figured out how to couple data from the monitors with data from the logistics system. The latter was essential for the daily operation of the department, and any changes in the admission flow of patients was instantaneously updated in the logistics system.

As portrayed by Figure 3, the PDWS was made available to clinicians using 24" all-in-one computers running Chrome OS. Nine of these were installed in offices at the ED of OUH, and six at the ED of HSWJ. Each computer was installed in the vicinity of the existing patient monitoring overview screen, and the clinical logistics system.

## Discussion

As clinicians become increasingly reliant on computers to filter and present data, a sensible balance of work shared between information systems and clinicians must be sought. In

this project, we sought to do so by simplifying a few of the streams of data that demanded the attention of clinicians, thereby aiming to mitigate the risk of information processing overload. The CRT is currently ongoing, and some preliminary observations are worth discussing.

### Workflow Integration and Information Habits

Several aspects of the PDWS design philosophy, especially non-intrusiveness, and the assumption that clinicians will automatically utilize a novel system tailored to specifically address a problem most are familiar with in the settings, appeared to be challenged in the CRT. Self-evident as it may be, it became strikingly clear that installing yet another computer screen in the cramped work spaces of most clinicians did not offer much of a head start for evaluation of a new health information system. In most of the ED offices, the PDWS screen mentally disappeared in the clinicians information landscape. Furthermore, evaluation of new systems that aimed to enhance or replace existing systems, which were already highly embedded in current practice, was complicated. Old habits die hard, as was also evident by information acquisition. Essentially, the aim should be to make information acquisition easier with new system, rather than the old one. Deciding to obstruct access to systems already in use is seldom feasible, rather the alternative is to make the new noticeably easier to use. Several participants proposed embedding the PDWS components into existing IT solutions. This would however make it considerably more complex to conduct a targeted effect evaluation review.

### Integration with Existing Information Systems

The real-time utilization of information from other hospital information systems, raised some concern amongst the organization. Legitimate concerns regarding unknown side effects were raised based on the new approach in utilizing existing systems. The solution was to conduct a PDWS code and performance audit on the supplier side to ensure that the PDWS did not strain existing resources or add risk.

### Continuous Emphasis on Purpose and Aim

Two other crucial aspects we strived to address, which also relate to the issues above, were training in system use and awareness of intent and purpose. Prior to the CRT, the project and system was introduced to clinicians through newsletters, employee meeting presentations, and posters adjacent to each

screen. During the intervention periods we conducted several walkthroughs of the system. Still, we found that a major percentage of clinicians refrained from relating to the system. Project staff (nurses and nurse assistants), despite extra training and expressed enthusiasm in the objective of the PDWS, were generally hesitant to act as system ambassadors in relation to coworkers. This points to the need for continuous emphasis on the purpose of systems research in the settings, and awareness of the implications of employee turnover.

### Future Directions

In several of the Danish Regions, work has been initiated to integrate data from medical devices faster and more seamlessly into decision making. Medical device data are to be enriched with data from other information sources (e.g., attending clinician, ordering speciality, patient info) to improve clinical, managerial, and operational services. The application of device utilization in the PDWS project, may serve as inspiration for new abnormality metrics. For example, raising flags when an abdominal ultrasound is ordered for a patient when it is not a part of the expected treatment plan.

### Conclusion

Organizational, cultural, and technical aspects influence the detection of patients at risk of deterioration. Current patient monitoring solutions have shortcomings regarding incorporating the temporal and spatial organization of clinical work. A substantial ratio of automatically registered vital signs should be triggering more clinical concern than what is being observed. Coupling this with the fact that monitoring of patients in an ED is highly skewed, and that temporal trends are hard to derive from existing monitoring solutions, points to the need for better visualization tools.

Based on experiences from this work, we recommend that similar initiatives seek to: 1) *Carefully assess the settings of each installation point* to increase integration with existing workflows and information habits. 2) *Strive to establish interdisciplinary partnerships through embedded presence* to greatly improve the project momentum. Similarly, performance, load analysis, and openness regarding code reviews of integration points with external hospital information systems should be leveraged with stakeholder concerns. 3) *Continuously emphasize purpose and aim of a project and system*, as the typically high employee turnover in hospital departments, challenges long-term projects driven by user involvement. Consequently, a continuous effort is required to imprint the purpose of both research aim and the purpose of the evaluated information system.

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