More isn't always better: Technology in the intensive care unit

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Background: Clinical care in modern intensive care units (ICUs) combines multidisciplinary expertise and a complex array of technologies. These technologies have clearly advanced the ability of clinicians to do more for patients, yet so much equipment also presents the possibility for cognitive overload.

Purpose: The aim of this study was to investigate clinicians' experiences with and perceptions of technology in ICUs.

Methodology/Approach: We analyzed qualitative data from 30 interviews with ICU clinicians and frontline managers within four ICUs.

Results: Our interviews identified three main challenges associated with technology in the ICU: (a) too many technologies and too much data; (b) inconsistent and inaccurate technologies; and (c) not enough integration among technologies, alignment with clinical workflows, and support for clinician identities. To address these challenges, interviewees highlighted mitigation strategies to address both social and technical systems and to achieve joint optimization.

Conclusion: When new technologies are added to the ICU, they have potential both to improve and to disrupt patient care. To successfully implement technologies in the ICU, clinicians' perspectives are crucial. Understanding clinicians' perspectives can help limit the disruptive effects of new technologies, so clinicians can focus their time and attention on providing care to patients.

Practice Implications: As technology and data continue to play an increasingly important role in ICU care, everyone involved in the design, development, approval, implementation, and use of technology should work together to apply a sociotechnical systems approach to reduce possible negative effects on clinical care for critically ill patients.

Key words: Critical care, qualitative, sociotechnical systems, technology implementation

Intensive care units (ICUs) provide medical care to critically ill patients. Originally designed to treat failures of single-organ systems (Weil & Tang, 2011), ICUs soon evolved to handle a wider range of acute conditions. Care in modern ICUs now combines multidisciplinary expertise and a complex array of equipment and technology (Marshall et al., 2017). These technologies, which on average generate over 1,000 data points daily per ICU patient (Manor-Shulman et al., 2008; Meissen et al., 2022), have clearly advanced clinicians' ability to care for patients by enabling precise monitoring for early complication detection, facilitating efficient treatment strategies, and providing advanced life support systems and real-time data analysis (Weil & Tang, 2011).

Although ICU technologies hold promise for advancing patient care, their potential to hinder it arises when these technologies lack adequate usability or generate excessive interruptions (National Academies of Sciences, Engineering, and Medicine et al., 2019). Having so much equipment can facilitate sensory and cognitive overload (Wung et al., 2018) and contribute to what some describe as "the hostile environment of the ICU" (Donchin & Seagull, 2002, p. 316). Prior ICU studies have raised concerns related to alarm fatigue (Lewandowska et al., 2020) and increased documentation time because of electronic health record (EHR) adoption (Osajiuba et al., 2021), one result of which is increased clinician burnout (Melnick et al., 2021). This burnout reduces clinician satisfaction and their ability to provide quality patient care (Hodkinson et al., 2022; Jun et al., 2021).

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Considering the plausible advantages and disadvantages involved is critical to understanding the role of technology in ICUs. To learn more about how technology impacts clinicians and the patient care they provide, we interviewed 30 clinicians to better understand their experiences with and perceptions of technology in ICUs and to provide insights into what works for technology implementation and where there are opportunities for improvement. Although our interviews acknowledged positive aspects of technology and the value technologies contribute to patient care in ICU settings, we focus in this study on clinicians' concerns and recommendations for how to mitigate them. Our interviews suggest that the amount of technology ICU clinicians confront is so great that it may create problems. Although some challenges with technology in the ICU arise from problematic design of individual technologies, such as poor human-centered design, many problems result from lack of integration among technologies, often because each is designed as if it will stand alone yet is deployed into complex, tightly coupled systems (Sutcliffe, 2011). In addition, learning to use each new technology requires time and attention from clinicians, who are heavily cognitively burdened and time constrained (Laxmisan et al., 2007). The widely anticipated arrival of more artificial intelligence-enabled technologies could ameliorate or exacerbate these issues depending on how they are designed, developed, implemented, and maintained within the ICU. In this article, we apply a sociotechnical systems (STS) framework (Trist, 1981) to understand clinicians' concerns and suggestions to improve technology implementation and adoption in ICUs.

Theory

Implementing a new technology in complex systems depends on its successful integration into existing workflows (Karsh, 2004). In health care, not considering clinician–technology and technology–technology interactions can adversely impact patient safety (Ruppel & Funk, 2018). STS theory, first introduced in the 1950s and subsequently updated and extended to a variety of disciplines and domains, addresses these concerns (Trist, 1981). STS theory emphasizes that organizations consist of both social (people, attitudes, culture, relationships, experiences, and management/leadership) and technical (knowledge and tools used to undertake work) systems and that these two systems and interactions within each, between them, and with their environment impact organizational outcomes. The same technology can produce different results based on how well it aligns with the social system of the organization in which it is introduced (Mumford, 2006; Pasmore & Khalsa, 1993; Trist et al., 1963).

To balance the needs of social and technical systems, research suggests that organizations should strive to achieve "joint optimization," meaning that both social and technical systems are designed and operated to maximize a unified goal or set of goals. Optimizing social and technical systems individually will lead to suboptimization of the entire system (Di Maio, 2014; Emery, 1959; Trist, 1981).

Although STS research is relatively well recognized in fields such as engineering (Di Maio, 2014), information technology and systems (Lee et al., 2008), and manufacturing (Mumford, 2006), it has only recently become popular in health care. Recent applications include using an STS approach to help improve EHR usability and decrease clinician burnout (Carayon & Salwei, 2021), to better understand interruptions in the emergency department (Werner & Holden, 2015), and to inform the design of a personal health information management system for patients (Werner et al., 2020). Despite growth in applying an STS approach in health care, most research has focused on specific technologies solely (e.g., EHR systems; Carayon & Salwei, 2021) or a single phenomenon (e.g., interruptions; Werner & Holden, 2015). There has been limited research utilizing an STS lens to consider the entirety of the technologies present in a setting like the ICU. Addressing this gap is important because as critical care continues to evolve, technologies are playing an increasing role in ICUs, and how they are implemented and integrated within the social and technical systems of the ICU will be increasingly important. With this study, we begin to fill this gap, and in doing so, we show how applying an STS approach can support implementation of new technologies in critical care.

Method

Study Design and Setting

This study is part of a National Science Foundation-funded project studying the clinical, behavioral, operational, and economic impacts of technology in ICUs to inform development of innovative hardware, software (algorithms), and organizational and operational methods to assist workers in safety–critical daily work. Our study was approved by the Stanford School of Medicine institutional review board. Our study team is multidisciplinary, including two physician-scientists and five nonclinicians with expertise in health care innovation, organizations, and operations research.

Data for the present study come primarily from semistructured interviews with clinicians and frontline managers who work in four ICUs at a large, academic medical center in the United States that has been an early adopter of technology (Rogers, 1995). Informal observations (100+ hours) in the work units provided essential contextual background for leading and understanding interviews.

A key aspect of the STS approach is to give those involved with and affected by the technologies a voice in design and decision-making processes (Mumford, 2006). Because we sought to understand how clinicians describe their experience with and perspectives of technology, a qualitative approach focused on clinicians who use technologies in the ICU is appropriate.

Study Sample

We studied four medical/surgical ICUs, two of which were scheduled for future installation of video-monitoring technology, which could be used for computer vision and artificial intelligence activities. We invited clinicians, managers, and administrators from the four ICUs to participate in interviews. We sought a diverse sample, targeting nurses more than other clinician roles because of their physical presence and interactions with the technologies of interest. We interviewed a total of 30 ICU clinicians and frontline clinician-managers, enough to achieve theoretical saturation

(Vasileiou et al., 2018), consisting of 11 nurses, six physicians, four advanced practice providers (physician assistants and nurse practitioners), two physical and one respiratory therapists, one pharmacy resident, four nursing patient care managers, and one administrator. Interviewees experience level ranged from less than a year to over 30 years. Most of our interviewees were assigned to and worked in a single ICU. The division of interviewees among the four ICUs was nine, eight, six, and two, with five interviewees who floated among multiple units. We invited ICU personnel to participate via e-mails sent by their managers. We also identified potential volunteers during ethnographic observations. In addition, we used a snowball approach, inviting interview subjects to identify additional interviewees (Goodman, 1961). When we noted gaps in our study sample or data, we conducted additional interviews using a focused interview guide to explore specific themes more deeply. We continued the interviews until we reached theoretical and data saturation based on the consistency and similarity of experiences reported (Saunders et al., 2018).

Data Collection and Instrument

Participation in interviews was voluntary, and all participants provided informed consent. Pairs of research team members conducted most interviews, with one asking questions and another taking notes. We conducted interviews via Zoom using written interview guides. We developed an initial interview guide based on current literature on technology adoption and implementation. We designed questions to promote discussion around interviewees' typical work shift, what supports or hinders them in work, their recommendations for improving ICU work, and their experience with new technologies in the ICU. We asked additional probing questions about a hypothetical future of video-monitoring technology that could detect and support clinicians at work.

After reviewing the data and findings from 20 initial interviews, we created a supplemental interview guide and conducted a second round of interviews to achieve theoretical saturation (Vasileiou et al., 2018). The supplement aimed to explore the specific themes of technology integration and disruption more deeply, better understand how technology supports clinicians, and gather more information on factors to consider when adopting technology, which were raised by interviewees in the first round. Interviews lasted between 30 and 80 minutes (mean = 55 minutes).

Data Analysis

We conducted data analysis using two approaches in sequence. Both used principles of thematic analysis (Braun & Clarke, 2006) to identify common themes, and they produced similar findings, enhancing their dependability (Guba & Lincoln, 1994; Lincoln & Guba, 1985).

First, one author reviewed the first round of 20 interview transcripts, applying an open coding approach, naming and organizing codes into thematic categories. Authors met with clinician-experts beyond the set of authors multiple times to better understand and discuss insights from the findings. We presented findings to ICU and hospital clinicians and administrators in multiple meetings (e.g., Patient Care Services Research and Innovation Council, ICU quality improvement committee, ICU management) to solicit feedback and assess credibility (Guba & Lincoln, 1994; Lincoln & Guba, 1985). The various meetings included some of the individuals who were interviewed, but the majority of attendees were not included as research subjects.

Second, authors applied a more formal approach to qualitatively coding the full set of 30 interview transcripts. Because the supplemental interview guide asked questions that probed deeper into themes discussed in the initial interviews, we included the relevant data from the interviews in our analysis. For the second more formal analytical approach, the authors developed coding guidelines based on (a) the findings from the initial coding process and (b) the feedback on those initial findings that we received from the clinician-experts we met with and the ICU and hospital clinicians and managers from the various meetings. A research associate used the coding guidelines to create an initial coding structure, which was updated iteratively by the team. We utilized MAXQDA 2022 software (VERBI Software, 2021) to code the interviews. The team then pulled the MAXQDA codes out of the software, reviewed the codes and data to identify common patterns and ideas, and grouped the codes into themes and subthemes. To establish confirmability (Guba & Lincoln, 1994; Lincoln & Guba, 1985), authors met regularly to discuss the data, questions, and coding decisions and interpretations and, after coding the interviews, to review the data, refine the themes into additional subthemes as needed, and discuss findings. To demonstrate research authenticity (Guba & Lincoln, 1994), we include an array of rich quotations in our results.

Results

When interviewees discussed technologies, they focused on information and communication technologies that support information sharing. Some of the technologies commonly discussed included the EHR, an encrypted text messaging platform for clinician and clinical team communication, wearable sensors for patient position monitoring, medication dispensing and administration systems, electroencephalogram video monitoring of brain activity, a monitor for time-synchronized multimodal data, and a tele-sitting device for remote audio/visual patient monitoring. Below, we (a) characterize the connection between social and technical systems in the ICU, (b) outline challenges associated with providing critical care in a complex STS, and (c) outline strategies that ICU workers offered to mitigate challenges and jointly manage social and technical issues.

Importance of Social Over Technical Aspects in the ICU's STS

Interviewees consistently emphasized the importance of social versus technical factors, that is, the "human aspect" of ICU care. Many interviewees emphasized that their team members are the thing that supports them most at work. They also discussed how technology will never be able to replace some aspects of ICU care, such as the ability to understand the clinical context and patient-specific nuances and the empathy clinicians must be able to provide to patients and their families:

I would just say that a lot of the work in the ICU that is not captured by machine, that is not captured by charting, that is not captured by protocols is the human side […] How do you talk to a family member that has a family member in the ICU? […] having the skill set to communicate and guide some goals of care discussion, or be empathetic, or be sensitive to that heightened state […] that's the work that takes years to master. And that's something that unfortunately machines are never going to be able to do… (Physician, Int. 3)

Challenges Associated With Providing Critical Care in a Complex STS

The overarching theme across interviews was that, although technology can be very useful in caring for patients and generally supports ICU clinicians in their work, many technologies cause frustration, can be overwhelming, and can adversely impact clinicians' ability to provide patient care. As one clinician described, "This [technology] could have been helpful, but it's also now interfering with other aspects of care" (Physician, Int. 9).

We categorized clinician frustration with new technologies in the ICU into three challenges: (a) too many technologies and too much data; (b) inconsistent and inaccurate technologies, especially when compared with clinicians' abilities and decision-making skills; and (c) not enough integration among technologies, alignment with clinical workflows, and support for clinician autonomy. Table 1 summarizes these challenges and their impacts on ICU care. We discuss each in turn.

Challenge 1: Too many technologies and too much data. The number of distinct technologies and data available in the ICU can lead to information overload and disruptions, which impacts clinicians' ability to complete their work and care for patients. There was a feeling that when it comes to technology in patient care, more is not always better: "I just don't necessarily feel like you need to add more things [devices] on the patient. You need to take things off, not keep adding stuff on" (Nurse, Int. 22).

Clinicians reported that too many technologies in the ICU cause significant complexity and make providing care harder. Provider preference contributes to this challenge when individual clinicians insist on using certain devices that only they use: "We have a ton of portable medical equipment […] And so we only use that when this doctor is here […] we literally have carts that are named after physicians that use them" (Administrator, Int. 1). As technologies accumulate, clinicians (especially nurses) must specialize in order to use the ones required for their patients. Pure physical excess of technology, that is, too many wires and tubes connected to patients, also raised concerns.

Information overload occurs when clinicians are inundated with too much data from technology. Clinicians struggle to translate the available data, all of which they are theoretically supposed to absorb into coherent information. This substantial amount of data available for each patient is particularly difficult for physicians who oversee care for many patients. "It's already an immense amount of data. […] we live in a very data rich environment in the ICU. And so I'm like… I can't possibly take in more data on 12 to 14 really complex patients" (Physician, Int. 24).

TABLE 1: Challenges with technology in the intensive care unit (ICU)

Challenges with technology in the ICU	Description of challenge	Impact of challenges on ICU work
Too many technologies and too much data	There are too many technologies that are not universally useful, are provider specific, or require specialized staffing. Technologies often provide too much data, provide it in a way that is difficult for clinicians to process, and lead to disruptions and alarm fatigue.	The quantity of technologies and data can be overwhelming and disruptive and can lead to information overload, which in turn impacts clinicians' cognitive capacity and ability to complete their work and care for patients.
Technologies can be inconsistent and inaccurate	Technologies fail technically, are not sensitive enough, and have inherent biases. Technologies are unable to understand patient-specific nuances, adapt to patients' needs, or identify when there is a need to deviate from a protocol.	Technologies' inconsistencies and inaccuracies increase clinicians' workloads and need for workarounds and lead to a distrust that technology will make the right decision.
Lack of tech–tech and socio–tech integration	Not all technologies integrate with the electronic health record or other technologies. Clinicians perceive that the way technology is currently integrated impacts their autonomy and decision-making.	Technologies' lack of full integration with other technologies and into the clinical workflow creates more work for clinicians and introduces the opportunity for errors. It is also perceived to negatively impact clinician autonomy.

Information overload and the potential it raises for cognitive oversights and errors are recognized problems (Nijor et al., 2022). Many technologies include methods to address them, such as alerts and alarms to warn when an input is out of the normal range and may be erroneous or dangerous. Alarms are built into technologies assuming that busy clinicians may not always notice problems. However, several interviewees said that the alarms can be too sensitive and not patient specific, which sometimes leads to clinicians ignoring them: "There are so many [alarms] that sometimes people just stop paying attention to it. They're just like, okay, where do I need to click to? I want this order, I don't care what this says, I'm just going to click on it so I can get through it" (Physician, Int. 9).

Another source of disruptions are communication technologies, such as phone and texting apps. These are helpful in facilitating conversations among care team members, but they can interrupt clinicians' train of thought, take up time, and pull clinicians away from other tasks. "There's this constant interruption, […] you may have been in a very deep thought over here about what's going on with your patient and this constant interruption keeps you from ever finishing" (Nurse Practitioner, Int. 11).

Challenge 2: Inconsistent and inaccurate technologies. This challenge arises when technologies do not work well technically, break or glitch, have inherent biases, or do not take into account patient- and context-specific nuances. These problems impact clinicians' trust in technologies and the amount of work clinicians need to do to compensate for shortcomings.

New technology may not deliver the functionality it claims. The time spent implementing and troubleshooting technologies can also take up a lot of time that could be spent on patient care. It is especially frustrating when a technology breaks or glitches.

Clinicians also recognized inherent biases that can affect algorithmic decision-making, such as bias in underlying data used to train machine learning algorithms or not considering the status of terminal patients when recommending doses of analgesics. Interviewees voiced general concern that technology alone is unable to adapt to different circumstances and to understand truly what is going on with the patient. Some reported less willingness to use technologies that do not adapt for patient-specific nuances and contextual factors that impact ICU care the way that experienced clinicians do. Interviewees described not wanting to be misled by technologies, and some felt that current technologies are not yet sophisticated enough to discern the nuances that clinicians use to make decisions in the ICU. Overall, there was a belief that the human aspect of clinical decision-making cannot be replaced by purely technical solutions because "what you do with patients is very, very personal and individual. And it's hard to generalize that with code" (Nurse Practitioner, Int. 19).

Challenge 3: Not enough integration among technologies, alignment with clinical workflows, and support for clinician autonomy. The third problem that interviewees frequently discussed was that as new technologies are layered one on top of the other, they often do not get integrated with each other or with the EHR, and they do not integrate well with clinical workflows or support clinician autonomy. Lack of integration among technologies and the EHR leads clinicians to spend additional time with documentation:

> *A lot of information which is on the machines […] it does not get translated into documentation, so we […] start digging into the chart, because somebody reads those monitors, enters them into Epic, and we open the Epic and read the same data and then put it in our note. There are like five steps to something that [should] just flow very nicely. (Physician, Int. 17)*

This lack of integration also leads to clinicians needing to check different locations or even verbally ask for information, which adds time, tasks, and opportunities for error to their work. In addition, even after a technology has been integrated with the EHR, clinicians report having to double check it to confirm accuracy.

> *We sometimes get lab values that are automatically loaded into the system that don't make any sense whatsoever. And it's just something that the computer is automatically transmitting. Even if the machine is unplugged, it continues to transmit data. […] And so you always have to double-check that those readings that are outside the range of normal limits are real. (Pharmacy Resident, Int. 14)*

Not only are technologies poorly integrated with other technologies, but technologies have also not been integrated well into clinicians' standard workflows and therefore create more work for clinicians. By adding more work to clinicians' workload, technologies can limit the time clinicians have to focus on providing care to patients. Technologies create more work when they add tasks that are perceived not to be helpful, are not intuitive, and require clinicians to modify their workflow to meet the needs of the technology. As explained by one nurse, "The way that technology is made, it's not effective in what it's trying to do. And it just creates more mundane tasks" (Nurse, Int. 2).

Advancements in technology have also enabled clinicians to extend their workflow and take work home with them, which allows them to work long hours, contributing to burnout: "They call it 'work after work.' So you have your whole workday and then you have a few hours to yourself and then you're doing more work because you're back on Epic from home […] your work day is never ending" (Physician, Int. 18).

In addition, the way technologies are currently integrated in workflow is perceived to hinder clinicians' professional autonomy and decision-making ability. Interviewees expressed concerns that new technologies would be used to monitor them and hold them accountable internally and even externally in legal cases. Interviewees expressed concerns about how the increase in accountability associated with an increase in video-monitoring technologies could lead to a decrease in clinician autonomy by calling into question the decisions they make. When their decisions are questioned after the fact, in the best case, it is a hassle, and in the worst case, it could have major repercussions to their medical career. In the end, interviewees value their ability to be clinical decision-makers and are concerned that technology could impact this aspect of their role.

> *I think it [camera monitoring] would create more distrust within the hospital. Now your employers are spying on you, and there's no longer autonomy because Big Brother is watching you. Your whole point of being an independent practitioner is that's your judgment call. You were trained, it's your license [...] to do those things. (Nurse, Int. 12)*

It is not just nurses who are concerned about the impact technologies may have on their autonomy and decision-making. One physician explained how technology that records clinician and patient/family interactions can sometimes impact clinician autonomy in that it can also change clinician behavior. There is a concern that this impact on autonomy will change the clinical environment by leading to punitive measures:

> *It changes the feeling in the room, and it changes the interactions between the family and the care team. The care team gets very nervous that they're going to make a mistake and inhibited in communication because they don't want to say the wrong thing. And that also takes away from the doctoring, I think, in some cases. So how we find the balance in this I think is really a challenge for the next 50 years. (Physician, Int. 24)*

Strategies for Mitigating Challenges and Jointly Optimizing Social and Technical Systems

To address the three technology-related challenges described above, clinicians offered suggestions for mitigation that revolved around improving either the social or technical systems, that when implemented together could lead to improved joint optimization of both systems. One nurse explained why considering both the social and technical systems is so important. When discussing the liability associated with the increase in technology that monitors nursing work, a nurse explained: "Nursing isn't [...] structured to be cut and dried the way that our technology is" (Nurse, Int. 29), meaning that sometimes technology falsely alarms or is incorrect, and nurses need to deviate from care guidelines. This is not something that technology is currently able to do or understand. However, because nursing is structured to pull in additional information from interactions with other clinicians and with patients and their families, it is more person-centered and relies on inherently human interactions that technology is not currently able to emulate. Therefore, utilizing information from the social and technical systems is important for mitigating challenges associated with technology in the ICU.

Mitigation strategies for too many technologies and too much data. Table 2 lists one technical solution and three social solutions for addressing the first challenge.

Ensure new technologies do not contribute to information overload

There are several ways to prevent new technologies from contributing to information overload. One way is to avoid adding new technologies to address problems, instead finding ways of modifying current technologies to accomplish tasks or utilizing technologies that perform multiple tasks. Another way to help with the vast amount of data and technologies is to use technologies in ways that are helpful for clinicians, such as monitoring patients and identifying trends in their data, to support better informed medical decision-making. Presenting the data in this way could reduce the cognitive load on clinicians. "I would like it to tell me how my patients are continuing in their continuum of care. Are these patients getting better? Are these patients getting worse? Is this patient likely to die or survive? I would like it to tell me how this patient's going to be doing in 48 hours so I can act on that" (Physician, Int. 3).

Ensure clinicians understand how to interpret data

Sometimes clinicians feel there is too much data because they are unable to understand, interpret, and use all the data. This concern can be mitigated by helping clinicians interpret the data correctly. Training clinicians both about the use and limitations of a technology and how to interpret its data is one way to make sure this happens: "We have to make sure that the people who are using it [a new technology] know how to deal with those numbers, know what they mean, what they don't mean, and just interpret it carefully" (Physician, Int. 9).

Ensure new technologies do not increase disruptions to clinical workflows

Interviewees expressed the importance of considering the impact of disruptions to their workflows. To ensure that new technologies do not unnecessarily increase disruptions, interviewees requested that thresholds be tailored to ensure alarms are for big problems and are customizable for patients. In addition, it would be helpful if when alerts were set up, they were created to go to the person who could respond to them. The current alert process with the nurse as a "middle-man" disrupts the nursing workflow, and impacts nurses' satisfaction.

> *If there was some way we could take the nurse out of there as the middleman, and just put the reminder directly to the physician [...] I think that would help a lot with nurse satisfaction. Just making sure that the alert goes to the person who can really resolve it, and not involve people that just have to be a messenger to go tell someone. (Patient Care Manager, Int. 6)*

Although removing the nurse as the intermediary may improve nurse satisfaction, it is unclear how it would impact physician workflows and so would need to be investigated prior to implementation. Also, clinicians reported value in allowing flexibility when it comes to alerts, because they sometimes need to go off protocol as part of the patient care

TABLE 2: Mitigation strategies for too many technologies and too much data

Type of solution	Recommendation theme	Recommendation description
Technical system solutions	Ensure new technologies do not contribute to information overload	Instead of always adding new technologies, try to find ways to modify existing technologies
		Use technologies to present trends in an intuitive way and predict patient health status
		Use technologies to monitor other technologies
Social system solutions	Ensure clinicians understand how to interpret the data	Train clinicians to understand the limits of a technology and how to interpret its data
	Ensure new technologies do not increase disruptions to clinical workflows	Tailor thresholds for alerts for big misses, important information (i.e., medications), or patient-specific values
		Set alerts to go to the correct person
		Provide information while still allowing flexibility
		Provide the "why" for the alert
	Incorporate technologies into the clinical workflow	Set up workflows for use of new technologies

process. They also reported that knowing the "why" or reason behind a warning could decrease frustration with the warning itself.

Incorporate technologies into the clinical workflow

Finally, concerns about too much data and too many technologies can be ameliorated if the social system surrounding new technologies were considered and the technologies were better incorporated into clinician workflows. Several examples illustrated opportunities for enhancements. First, clinicians sought integration of spontaneous breathing trial data into the EHR; despite technical capacity, the connection for information transfer had not been established. Second, although wearable sensors notified nurses that patients' position needed adjustment, it did not provide the assistance that would enable the nurse to accomplish the task. Third, new in-room video-monitoring technology enabled providers outside a patient room to speak to a patient or provider in the room, and clinicians described a desire to enable family members outside the institution to use the technology.

Mitigation strategies for inconsistent and inaccurate technologies.

Table 3 refers to one technical and one social solution for addressing the second challenge.

Ensure that new technologies work, are consistent, and can adapt to patient specific needs

To address the challenge of inconsistent and inaccurate technologies, health care managers need to ensure the technologies they are implementing work and work well. One cautionary tale shared explains:

> *They tweaked the technology somehow and [...] it didn't work great. [...] We were collecting all of them to return [...] They were not really available for weeks. Then trying to get everyone back up and running on [technology] has been painful. [...] They were unreliable, then they weren't available. People never liked them anyway, so when they disappeared, not a single person shed a tear, from a manager to a bedside nurse. [...] (Patient Care Manager, Int. 30)*

In addition, interviewees reported wanting technologies to be able to meet the needs of their specific patients by (a) creating technology that adapts to patient needs and (b) setting exclusion criteria that ensure patients who do not need a new technology are not forced to use it.

Adoption and use improve as clinicians begin to trust the technologies

Consistency and accuracy are important for new technologies because if technologies consistently make the right call, interviewees believe that clinician adoption will increase.

Mitigating the integration challenges.

Table 4 lists two technical and two social solutions that could address the third challenge.

Integrate technologies with the EHR and other technologies

To address concerns about lack of integration, interviewees requested that new technology be integrated with (a) the EHR to reduce duplicative work and (b) other technologies already in the ICU. If all technologies could respond to the signals of other technologies, providers felt the technologies could help offload their patient care tasks.

> *I think technology that is integrated, but also technology that speaks with other… like speaks with all the machines in the room. Like the Internet of things [...] everything that's integrated will offload the*

TABLE 3: Mitigation strategies for inconsistent and inaccurate technologies		
Type of solution	**Recommendation theme**	**Recommendation description**
Technical system solution	Ensure new technologies are consistent and can adapt to patient-specific needs	Technologies should work and fit patients' needs: Allow exclusion criteria based on patients' condition and/or adjust to patients' current situation
Social system solution	Adoption and use improve as clinicians begin to trust the technologies	Adopt technologies that prove to be reliable

provider better. So I think that to an extent, integrating all the different sensors in the ICU room so they're connected to one another and can then respond to one another. (Physician, Int. 3)

Increase automation and integration of technologies to decrease work and workarounds

Integration also improves as automation of manual tasks increases. When discussing their work tasks within the ICU, interviewees consistently reported that documentation occupies a large portion of their day, and documentation support was most commonly discussed as a way that technologies could better support clinicians in their daily activities. Interviewees discussed using voice/dictation, artificial intelligence/algorithms, and computer vision as methods of relieving their documentation. They were especially interested in finding a way to automate documentation by integrating technologies with the EHR, which could remove some of the duplicative work they do, stating: “Nurses would appreciate any kind of automation that you could do, that didn't require them having to go in and do it, but somehow gathered the information and put it in directly” (Patient Care Manager, Int. 6).

Automation can also improve the nonclinical aspects of documentation, including identifying billing codes for physicians and reducing time spent auditing patients' charts. Integrating tasks into technologies through automation could greatly offload clinicians' current work and free up their time for patient care. Automation is not only beneficial for documentation purposes; it can also minimize errors in patient

TABLE 4: Mitigation strategies for integration challenges		
Type of solution	**Recommendation theme**	**Recommendation description**
Technical system solutions	Integrate technologies with the electronic health record (EHR) and other technologies	Integrate technologies with the EHR to reduce duplicative work
		Integrate technologies with each other and incorporate data gathering into current technologies
	Increase automation and integration of technologies to decrease work and workarounds	Integration can help automate documentation-related tasks
		Integration of standards/guidelines within technologies can help automate double checks for safety
		Integrated technologies will be a better able to provide information and assistance when needed
Social system solutions	Ensure work is easier for clinicians to improve integration into workflow	Ensure the work is worthwhile and will be easier or add value in the long run
	Address privacy and autonomy concerns to improve integration in clinical workflow and clinician identity	Enable mechanisms to protect patient privacy with video-monitoring technologies
		Show providers the output from monitoring technologies
		Use the output from monitoring technologies to improve work but not to punish clinicians
		Demonstrate the technologies are necessary for patient care
		Over time, concerns decrease

care. When technologies are integrated with each other, they will be better able to automatically provide clinicians with either information or assistance when they need it.

Ensure work is easier for clinicians to improve integration into workflow

Another way to improve the social system is to ensure that new technology does not generate additional workload. Interviewees recognized that improving patient care often involves adopting new technologies that may add to their work. But with clinicians at or beyond the brink of tolerance for being overwhelmed and burning out, interviewees implored managers to emphasize time and effort saving technology over anything that added to their workload. Clinicians are more likely to "like new things if it's going to make our lives easier" (Nurse, Int. 8). By communicating how technologies can make frontline work easier or patient care better, managers can also facilitate greater acceptance of technologies within the social system of the ICU.

Address privacy and autonomy concerns to improve integration in clinical workflow and clinician identity

When it comes to new technologies, interviewees expressed the importance of integrating technologies with their views about privacy and autonomy. Interviewees believe in the importance of protecting patient and clinician privacy, and they expressed concerns with technologies that monitor patient care activities, especially video-monitoring technologies. For concerns about patient privacy, one method of mitigation includes integrating guidelines about when a camera could be turned off into the standard of care when using monitoring technologies.

To address concerns related to how technology impacts clinician autonomy, managers can show clinicians the output from technologies and how it will be used to help clinicians understand what is being monitored and why there is value in monitoring it. Setting clear guidelines for how outputs of technologies will be used can impact the willingness of clinicians to use the technologies and the culture surrounding the technologies. Ensuring that technologies will be used for improvement, but not individual punishment, is key to integrating technologies into a safety culture. "I think education around what the output is, what it looks like, and then what you all are going to do with it. I think again, privacy concerns are just going to be the biggest thing. Then also making sure that, that doesn't get translated into penalties for anybody, God forbid there's a bad outcome" (Physician, Int. 18).

Privacy concerns are also ameliorated when clinicians understand that the technologies are necessary for improving patient care, "If it's needed […] what do we do?[…] If it's necessary for patient care, if it's going to relieve some of the ongoing issues that you have, and it's going to help alleviate those issues by having this implemented, then I don't have any issues with those" (Nurse, Int. 4).

Finally, it may just take time to assuage clinicians' concerns about privacy.

General mitigation strategies. In addition to the strategies offered to mitigate the specific challenges described, clinicians also identified general ways that technologies could improve their work. One way technology can better support clinicians is by providing logistical data and support, such as tracking clinician movements and actions to provide objective data to identify appropriate staffing levels based on patient acuity. Interviewees also explained that improvements could be made in the design process to improve the technology by talking with frontline staff about what their needs are. This would mean actively engaging clinicians in design and implementation decisions.

Many interviewees recommended commonly known best practices to consider when incorporating new technology. These included finding champions for the technology and its implementation, training staff on how to use the technology, creating tip sheets and making it easy to find help with the technology, doing phased rollouts/pilots with technical teams on site, and finally ensuring everyone uses the technology.

Finally, to improve buy-in and use of new technologies, interviewees stressed the value of ensuring the technologies not only improve patient outcomes but also that those results get shared back with those using the technologies. In this case, communication between frontline staff, frontline managers, and quality improvement teams is key. Doing this could increase clinician willingness to use the technologies, and not doing so can lead to discontent and lack of use.

> *If there is actual information […] that it's truly helping our patients, that's not getting disseminated back to the bedside nurses […] I think a lot of us would shut up about complaining about it, if we actually had data that validated that this really does improve patient outcomes […] I have not heard any of that information. (Nurse, Int. 12)*

Discussion

In this study, we sought to better understand clinicians' experiences with and perceptions of technology in ICUs. New technologies are essential to ICUs' ability to manage severe illness, injuries, and complications and indeed were one rationale for the early use of ICUs (Meissen et al., 2022). New technologies have clearly improved care and saved lives (Weil & Tang, 2011). However, our research identified a paradox: While acknowledging benefits of technology, many interviewees also viewed some technologies as problematic and somewhat detracting from their ability to care for patients. By applying an STS approach, this study characterizes strategies that could mitigate technology-related challenges and optimize potential benefits of technologies in the ICU.

Like many health care delivery organizations, the large academic medical center in which we conducted this study often resolved issues that arose in its ICUs by seeking a technical or technology solution. However, when interviewees discussed what supports them most in their work in the ICU, they consistently emphasized their social systems, that is, the role their team and team members play in assisting them. This discrepancy suggests that the inclination to fix problems by adding to the technical systems (but not the social system), while disregarding the integration of technology with existing workers and workflows, may be a suboptimal approach to achieving sociotechnical balance. In fact, adding new technologies can lead to frustration and feeling overwhelmed. These findings highlight the significance of integration for jointly optimizing social and technical systems and supporting clinicians' satisfaction (Emery, 1959; Trist, 1981). To achieve joint optimization, ICU leadership should consider a range of potential ways to use technologies, including as supplemental, adjunctive aides rather than seeking to supplant clinician judgment.

Previous research suggests that involving future users in the design, development, and implementation of new technologies can increase the likelihood of successful integration into the existing work flows (Ruppel & Funk, 2018). Using an STS approach that balances between the technical and social systems to integrate technology can improve clinician workflow and decrease the number of unique devices clinicians engage with to find information needed for patient care. By involving end users, ICU managers can ensure added technologies are consistent and accurate enough to be trustworthy in patient care. Improving clinician trust in new technologies, including those incorporating artificial intelligence, is key to improving adoption and utility (Asan et al., 2020). ICU clinicians perform complex, high-stress work, and adding new technologies without integrating them means adding to their workload. Interestingly, the hospital in which we conducted interviews generally uses pilot studies and solicits feedback from frontline clinicians before rolling out new technology. However, interviewees expressed frustration with technologies that had gone through that process. Therefore, feedback from users should continue after implementation to ensure technologies continue to meet clinician and patient needs without adding undue burden.

In addition, this study occurred in the United States, where medical devices are regulated by the U.S. Food and Drug Administration's (FDA) Center for Devices and Radiological Health (FDA, 2020b). As part of the device development process, medical devices undergo a thorough process to help ensure that the devices are both safe and effective and to ensure that device developers follow appropriate manufacturing procedures (FDA, 2020a). In addition, the FDA provides guidelines for considering human factors and device usability, which includes guidance for considering device users, use environments, and user interfaces (FDA, 2016). However, even with the FDA's regulatory process and human factors guidelines, technologies and medical devices can cause frustration when implemented within a complex STS like an ICU. Perhaps this is exacerbated because the FDA focuses primarily on an individual medical device and its function, instead of evaluating the entire STS first and then considering the device's role.

It is important to recognize that our analysis also found that new technologies can add value in the ICU, especially when new technologies support patient care by providing clinicians with assistance in their routine daily tasks, helpful information for treating patients, or trends in patient data. Building on what works with technology implementations and following the mitigation strategies to jointly optimize social and technical systems can help improve patient care and clinician satisfaction while decreasing costs associated with failed technology rollouts and clinician burnout.

Managing technologies in the ICU is crucial for ICU clinicians and managers (Meissen et al., 2022). Our qualitative research gathers ICU clinician and manager perspectives to shed light on how to ensure technologies are relevant and useful, while not overburdening clinicians.

Limitations

Our research has several limitations. First, we studied a single academic medical center known for its research and early adoption of technological innovation. Similarly, the volume of technology implemented in ICUs tends to be greater than noncritical care units because of the complexity of the patients' conditions and the care associated with treating these patients, and therefore, our findings are limited to ICUs. However, technology adoption is already a business (Meinert et al., 2018) and moral (Hofmann, 2002) imperative in health care, and as technology continues to be introduced at an increasing rate to ICUs, we anticipate that many of the concerns and mitigation strategies expressed by our interviewees will be shared by their colleagues at other locations. Second, we asked interviewees about technology generally and probed for monitoring technologies (especially video-monitoring technologies). Given professionals' different roles and experience, there was variation in the technologies they had in mind when answering our questions, albeit most focused on information and communication technologies. Third, we did not measure actual behavioral effects of technologies, but only subjective reactions of users to them. Fourth, we understand that different clinical positions have different roles and tasks within the ICU and therefore different goals, expectations, and perceptions of how a given technology helps them achieve their work. In our interviews, we did not ask about role-specific technology, although some role differences did arise (e.g., providers who spent more time at the bedside expressed greater concern for video-monitoring technologies in patient rooms). We recommend that future research stratify and contrast clinical roles, apply an STS lens in the ICU and other health care settings focused on different technologies, and, recognizing that incremental change may not suffice, consider applying an STS approach to a zero-based redesign of the ICU. Finally, although our subjects were very patient-oriented, we did not investigate patient perspectives, outcomes, or experiences. Nor did we investigate perspectives of technology implementers or technology decision-makers, for example, Chief Medical Information Officers, whose perspectives might make a useful comparison.

Practice Implications

Our study findings suggest important implications for a variety of stakeholders, including technology developers and manufacturers, government officials regulating new medical devices, ICU managers, hospital technology purchasing and implementation teams, clinicians using new technologies for patient care, and patients whose care relies on successfully merging social and technical aspects of ICU care. None of these groups alone can solve the challenges we identified. All will need to contribute to truly improve the design, adoption, and use of new technologies in the ICU. The salience of these issues may increase as new algorithms incorporating artificial intelligence are introduced in a potentially haphazard manner.

Those developing and implementing technologies in the ICU should seek feedback from end users while also recognizing that not all of the suggestions provided by end users are practical and some may result in unintended consequences (e.g., removing the nurse as intermediary for alarms may increase physician alarms and alarm fatigue). Therefore, it is important to evaluate user feedback and provide transparency when suggestions are not implemented. In addition, suggestions from interviewees often focused on either social or technical system solutions. To achieve joint optimization, both systems should be considered and continuously evaluated at all stages of design through use. This will become increasingly important for health care leaders who could use an STS approach to evaluate how new technologies contribute to or detract from critical illness care.

As new technologies are added to the ICU, they have potential to both improve and disrupt patient care. Using an STS approach to jointly optimize the social and technical systems will be key to the future of ICU care. Understanding clinicians' perspectives can help identify strategies for optimizing both systems concurrently, which could help limit the disruptive nature of new technologies, so clinicians can focus more time and attention on caring for patients.

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References

Asan, O., Bayrak, A. E., & Choudhury, A. (2020). Artificial intelligence and human trust in healthcare: Focus on clinicians. *Journal of Medical Internet Research*, 22(6), e15154.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77–101.

Carayon, P., & Salwei, M. E. (2021). Moving toward a sociotechnical systems approach to continuous health information technology design: The path forward for improving electronic health record usability and reducing clinician burnout. *Journal of the American Medical Informatics Association*, 28(5), 1026–1028.

Di Maio, P. (2014). Towards a metamodel to support the joint optimization of socio technical systems. *Systems*, 2(3), 273–296.

Donchin, Y., & Seagull, F. J. (2002). The hostile environment of the intensive care unit. *Current Opinion in Critical Care*, 8(4), 316–320.

Emery, F. (1959). Characteristics of socio-technical systems. In E. Trist, H. Murray, & B. Trist (Eds.), *The social engagement of social science, Volume 2: A Tavistock anthology—The socio-technical perspective* (ed., pp. 157–186). University of Pennsylvania Press.

Goodman, L. A. (1961). Snowball sampling. *The Annals of Mathematical Statistics*, 32(1), 148–170.

Guba, E. G., & Lincoln, Y. S. (1994). Competing paradigms in qualitative research. In N. K. Denzin, & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (ed., pp. 105–117). Sage.

Hodkinson, A., Zhou, A., Johnson, J., Geraghty, K., Riley, R., Zhou, A., Panagopoulou, E., Chew-Graham, C. A., Peters, D., Esmail, A., & Panagioti, M. (2022). Associations of physician burnout with career engagement and quality of patient care: Systematic review and meta-analysis. *BMJ (Clinical Research Ed.)*, 378, e070442.

Hofmann, B. (2002). Is there a technological imperative in health care? *International Journal of Technology Assessment in Health Care*, 18(3), 675–689.

Jun, J., Ojemeni, M. M., Kalamani, R., Tong, J., & Crecelius, M. L. (2021). Relationship between nurse burnout, patient and organizational outcomes: Systematic review. *International Journal of Nursing Studies*, 119, 103933.

Karsh, B.-T. (2004). Beyond usability: Designing effective technology implementation systems to promote patient safety. *Quality and Safety in Health Care*, 13(5), 388–394.

Laxmisan, A., Hakimzada, F., Sayan, O. R., Green, R. A., Zhang, J., & Patel, V. L. (2007). The multitasking clinician: Decision-making and cognitive demand during and after team handoffs in emergency care. *International Journal of Medical Informatics*, 76(11–12), 801–811.

Lee, S. M., Kim, K., Paulson, P., & Park, H. (2008). Developing a socio-technical framework for business–IT alignment. *Industrial Management & Data Systems*, 108(9), 1167–1181.

Lewandowska, K., Weisbrot, M., Cieloszyk, A., Mędrzycka-Dąbrowska, W., Krupa, S., & Ozga, D. (2020). Impact of alarm fatigue on the work of nurses in an intensive care environment—A systematic review. *International Journal of Environmental Research and Public Health*, 17(22), E8409.

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Sage.

Manor-Shulman, O., Beyene, J., Frndova, H., & Parshuram, C. S. (2008). Quantifying the volume of documented clinical information in critical illness. *Journal of Critical Care*, 23(2), 245–250.

Marshall, J. C., Bosco, L., Adhikari, N. K., Connolly, B., Diaz, J. V., Dorman, T., Fowler, R. A., Meyfroidt, G., Nakagawa, S., Pelosi, P., Vincent, J. L., Vollman, K., & Zimmerman, J. (2017). What is an intensive care unit? A report of the task force of the world Federation of Societies of intensive and critical care medicine. *Journal of Critical Care*, 37, 270–276.

Meinert, E., Alturkistani, A., Brindley, D., Knight, P., Wells, G., & Pennington, N. de. (2018). The technological imperative for value-based health care. *British Journal of Hospital Medicine*, 79(6), 328–332.

Meissen, H., Gong, M. N., Wong, A. I., Zimmerman, J. J., Nadkarni, N., Kane-Gil, S. L., Amador-Castaneda, J., Bailey, H., Brown, S. M., DePriest, A. D., Mary Eche, I., Narayan, M., Provencio, J. J., Sederstrom, N. O., Sevransky, J., Tremper, J., & Aslakson, R. A. (2022). The future of critical care: Optimizing technologies and a learning healthcare system to potentiate a more humanistic approach to critical care. *Critical Care Explorations*, 4 (3), e0659.

Melnick, E. R., Fong, A., Nath, B., Williams, B., Ratwani, R. M., Goldstein, R., O'Connell, R. T., Sinsky, C. A., Marchalik, D., & Mete, M. (2021). Analysis of electronic health record use and clinical productivity and their association with physician turnover. *JAMA Network Open*, 4(10), e2128790.

Mumford, E. (2006). The story of socio-technical design: Reflections on its successes, failures and potential. *Information Systems Journal*, 16(4), 317–342.

National Academies of Sciences, Engineering, and Medicine; National Academy of Medicine; & Committee on Systems Approaches to Improve Patient Care by Supporting Clinician Well-Being (2019). *Taking action against clinician burnout: A systems approach to professional well-being*. National Academies Press.

Nijor, S., Rallis, G., Lad, N., & Gokcen, E. (2022). Patient safety issues from information overload in electronic medical records. *Journal of Patient Safety*, 18(6), e999–e1003.

Osajiuba, S. A., Jedwab, R., Calvo, R., Dobroff, N., Glozier, N., Hutchinson, A., Leiter, M., Nankervis, K., Rawson, H., Redley, B., & Manias, E. (2021). Facilitators and barriers to the adoption of an electronic medical record system by intensive care nurses. *Studies in Health Technology and Informatics*, 284, 510–515.

Pasmore, W. A., & Khalsa, G. S. (1993). The contributions of Eric Trist to the social engagement of social science. *The Academy of Management Review*, 18(3), 546.

Rogers, E. M. (1995). *Diffusion of innovations* (4th ed.). Free Press.

Ruppel, H., & Funk, M. (2018). Nurse–technology interactions and patient safety. *Critical Care Nursing Clinics of North America*, 30(2), 203–213.

Saunders, B., Sim, J., Kingstone, T., Baker, S., Waterfield, J., Bartlam, B., Burroughs, H., & Jinks, C. (2018). Saturation in qualitative research:

Exploring its conceptualization and operationalization. *Quality & Quantity*, 52(4), 1893–1907.
Sutcliffe, K. M. (2011). High reliability organizations (HROs). *Best Practice & Research Clinical Anaesthesiology*, 25(2), 133–144.
Trist, E. L. (1981). *The evolution of socio-technical systems: A conceptual framework and an action research program*. Ontario Ministry of Labour, Ontario Quality of Working Life Centre.
Trist, E. L., Higgin, G., Murray, H., & Pollock, A. (1963). *Organizational choice: Capabilities of groups at the coal face under changing technologies*. Routledge.
U.S. Food and Drug Administration. (2016). *Applying human factors and usability engineering to medical devices*. https://www.fda.gov/regulatory-information/search-fda-guidance-documents/applying-human-factors-and-usability-engineering-medical-devices
U.S. Food and Drug Administration. (2020a). *The device development process*. Retrieved April 7, 2023, from https://www.fda.gov/patients/learn-about-drug-and-device-approvals/device-development-process
U.S. Food and Drug Administration. (2020b). *Overview of device regulation*. Retrieved April 7, 2023, from https://www.fda.gov/medical-devices/device-advice-comprehensive-regulatory-assistance/overview-device-regulation
Vasileiou, K., Barnett, J., Thorpe, S., & Young, T. (2018). Characterising and justifying sample size sufficiency in interview-based studies: Systematic analysis of qualitative health research over a 15-year period. *BMC Medical Research Methodology*, 18(1), 148.
VERBI Software. (2021). *MAXQDA 2022*. maxqda.com
Weil, M. H., & Tang, W. (2011). From intensive care to critical care medicine: A historical perspective. *American Journal of Respiratory and Critical Care Medicine*, 183(11), 1451–1453.
Werner, N. E., & Holden, R. J. (2015). Interruptions in the wild: Development of a sociotechnical systems model of interruptions in the emergency department through a systematic review. *Applied Ergonomics*, 51, 244–254.
Werner, N. E., Tong, M., Nathan-Roberts, D., Smith, C., Tredinnick, R., Ponto, K., Melles, M., & Hoonakker, P. (2020). A sociotechnical systems approach toward tailored design for personal health information management. *Patient Experience Journal*, 7(1), 75–83.
Wung, S.-F., Malone, D. C., & Szalacha, L. (2018). Sensory overload and technology in critical care. *Critical Care Nursing Clinics of North America*, 30(2), 179–190.