The Future of Critical Care: Optimizing Technologies and a Learning Healthcare System to Potentiate a More Humanistic Approach to Critical Care

While technological innovations are the invariable crux of speculation about the future of critical care, they cannot replace the clinician at the bedside. This article summarizes the work of the Society of Critical Care Medicine–appointed multiprofessional task for the Future of Critical Care. The Task Force notes that critical care practice will be transformed by novel technologies, integration of artificial intelligence decision support algorithms, and advances in seamless data operationalization across diverse healthcare systems and geographic regions and within federated datasets. Yet, new technologies will be relevant and meaningful only if they improve the very human endeavor of caring for someone who is critically ill.

KEYWORDS: critical care; future; innovations; patient-centered care; technology

Heather Meissen, DNP, ACNP-BC, CCRN, FCCM[1]

Michelle Ng Gong, MD, MS[2,3]

An-Kwok Ian Wong, MD, PhD[4]

Jerry J. Zimmerman, MD, PhD, FCCM[5]

Nalini Nadkarni, PhD[6]

Sandra L. Kane-Gil, PharmD, MSc, FCCM[7]

Javier Amador-Castaneda, BS, RRT[8]

Heatherlee Bailey, MD, FCCM[9]

Samuel M. Brown, MD, MS, FCCM[10]

Ashley D. DePriest, LD, MS, RD, CNSC[11]

Ifeoma Mary Eche, PharmD, BCCCP, FCCM[12]

Mayur Narayan, MD, MPH, MBA, MHPE, FCCM[13]

Jose Javier Provencio, MD, FCCM[14]

Nneka O. Sederstrom, MPH, PhD, FCCM[15]

Jonathan Sevransky, MD, MHS, FCCM[1,16]

Jordan Tremper, MHA, BSN, RN, CCRN-K[17]

Rebecca A. Aslakson, MD, PhD, FCCM, FAAHPM[18,19]

written on behalf of the Society of Critical Care Medicine's Future of Critical Care Taskforce

HISTORICAL CONSIDERATIONS

Hypothesizing about the future of critical care is a difficult task. Predictions should be informed by the past while also advancing aspirations that are both pragmatic and inspirational. In 1854, during the Crimean War, Florence Nightingale enacted one of the first principles of critical care by placing the most seriously injured patients closest to the nursing station to allow for more attentive monitoring (1–3). However, it was not until the polio epidemic during the early 1950s and the advent of respiratory care units for polio patients confined to iron lungs that critical care medicine emerged. Max Harry Weil and Herbert Shubin in Los Angeles and Peter Safar in Baltimore created the first ICUs in the late 1950s. Since those early days, ICU organization and critical care practice have evolved extensively. Critical care clinicians have adapted to emerging science by implementing new techniques and have changed clinical practice when accumulating evidence failed to support previously accepted theories. Indeed, some aspects of care, such as the use of corticosteroids for sepsis, have had constantly changing cycles of acceptance and rejection driven by new and accumulating data or novel reconceptualization (4, 5). Regardless of ever-changing critical care practices and delivery, the critically ill patient remains the focal point in both the past and the future of critical care.

INTRODUCTION

Innovations in technology are invariably the crux of any speculation about the future of critical care. Although new technologies—along with better exchange

and use of data—will undoubtedly shape the future of critical care, they cannot replace the astute knowledge and humanistic clinician-patient interaction at the bedside. In the future, the multiprofessional critical care team will expand even further to harnessing emerging technology and data science tools across the continuum of critical illness from development to recovery. Future healthcare will seek to mitigate the current challenges of ineffective resource utilization, professional burnout, uneven distribution of services, and newly emergent complex syndromes/diseases by embracing smart technology, devices, and medications. Concurrent to this, clinicians will continue to ensure humanistic, patient-centered care with the right treatment for the right patient at the right time. Innovations will be meaningful only if clinical outcomes are optimized while patients and their families are treated humanely, compassionately, and equitably (**Fig. 1**).

Figure 1. Ideal state of the future ICU care team within a learning healthcare environment. *Care team is defined as all healthcare professionals and family or relevant support system. The family or relevant support system comprises individuals who can provide comfort to the patient outside of healthcare staff and may include direct family, friends, significant others, and/or religious leaders. Healthcare professionals include physicians, advanced practice providers, nurses, pharmacists, nutritionists, social services professionals, spiritual leaders, and physical, respiratory, and occupational health therapists.

A GLIMPSE OF THE FUTURE

A 59-year-old woman with fever and cough was diagnosed with influenza A by her primary care provider (PCP) 5 days ago. The PCP prescribed a wearable non-invasive continuous monitoring device. Today, the telehealth monitoring center is alerted by a surveillance artificial intelligence (AI) algorithm that demonstrates subtle signs of progressively worsening respiratory distress. A drone delivers initial therapies in response to this alert, but over the next few hours, the patient continues to worsen. The telehealth monitoring center contacts her, and the speech signal software detects irregularities that indicate respiratory decline. A mobile emergency care team is deployed to her home for further evaluation. The telehealth monitoring center notifies the patient's emergency contact and updates the contact on the next steps for care. The mobile emergency care team diagnoses bacterial pneumonia. Antibiotics are started but continuous monitoring and genetic and molecular biomarkers assessed through AI algorithms alert her clinical team that the patient is still at increased risk for respiratory failure and shock. The mobile emergency care unit continues treatment while transporting the patient to a hospital with appropriate capabilities and capacity. On arrival, her hospital care team begins an anti-inflammatory regimen that is personalized to her host response, the pneumonia, and the unique characteristics of the pathogen. To optimize efficacy and minimize toxicity, her medications are selected and dosed based on her genotype, patient-specific variables, and dynamic measures of drug response. She progresses to acute respiratory failure requiring intubation and is supported with mechanical ventilation
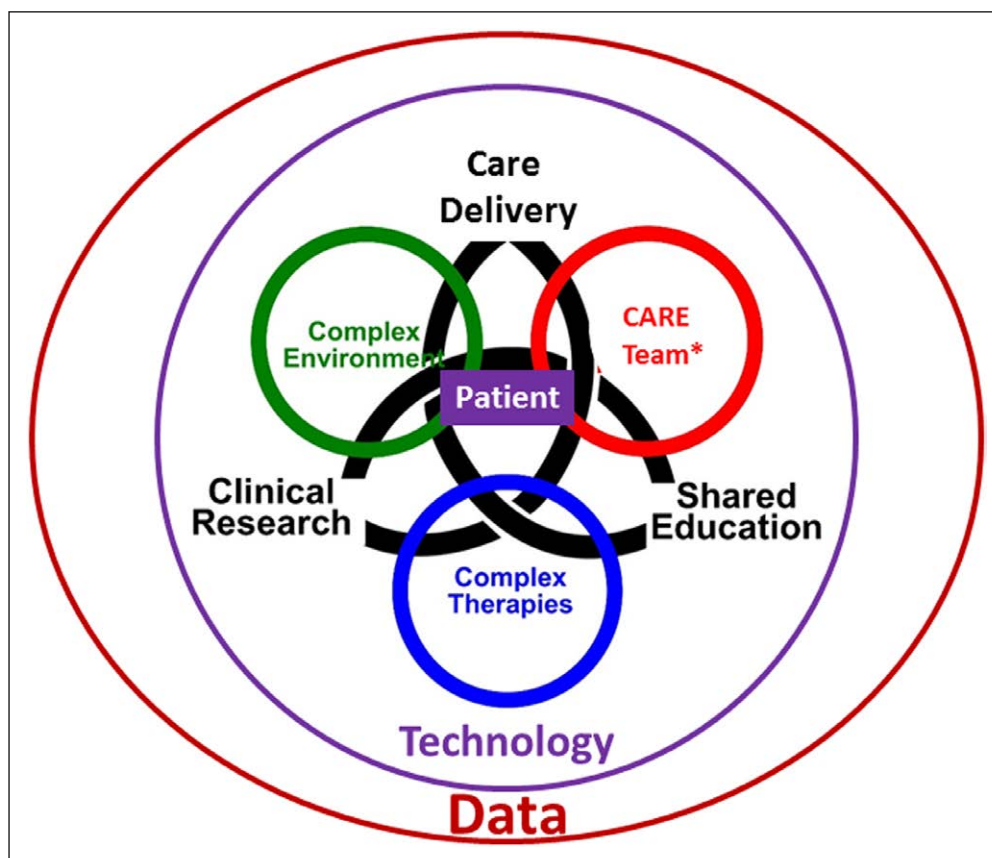
and infusion pumps equipped with closed-loop monitoring to enhance weaning and optimization of doses to effect. Her family is notified and, in compliance with institutional review board and ethics protocols, they consent to enrolling her in an embedded, multicenter, adaptive, clinical platform trial that is simultaneously assessing six interventions. All of her health data are securely aggregated with those from other patients with pneumonia for pandemic surveillance, continuous validation of machine learning algorithms, tracking of quality metrics, development of patient registries for certain diseases and conditions, clinical trial screening and participation, and public health monitoring.

HARNESSING DATA AND TECHNOLOGY TO IMPROVE DELIVERY OF CARE

Acquisition of data is integral to both modern life and modern healthcare. In the future, healthcare data will be harmonized and shared in real time to help healthcare professionals deliver precision care to improve both patient and population outcomes. Currently each patient in an ICU generates over 1,000 data points per day, in addition to conventional vital signs (6), and this will only increase with expanded use of advanced and remote monitoring systems from outside the ICU and hospital. Genomic and biological biomarkers as well as psychologic and social data will contribute to each patient's multifaceted data environment. As is happening in asthma (7) and cancer (8), precision medicine will enable identification and differential management of unique critical care endotypes (9) and responses to acute injury. Pharmacogenomic data will be combined with pharmacokinetic and pharmacodynamic predictive models to select a personalized medication regimen that incorporates prognostic factors and individualized patient phenotypes to mitigate potential side effects and optimize the likelihood of response to therapy. Technologies will be leveraged to better track and disseminate patients' social history and treatment preferences. Discussions undertaken in the prehospital setting regarding important patient preferences—such as advance directives, surrogate decision-maker(s), religion/spirituality, cultural beliefs, and preferred coping strategies—will be communicated across geographically and professionally diverse care teams and readily available to inform treatment choices.

Future paradigm shifts will be in data use rather than data acquisition. Data will not simply be stored in a database but will be actively processed for better real-time clinical decision-making. Vast amounts of data can lead to cognitive overload, which in turn can contribute to medical errors and burnout (10). Thus, it will be technology-assisted improvements in data management, integration, and presentation that will ultimately transform critical care practice. Data will be readily accessible in multifaceted permutations, such as individual patients, various patient groups, diagnoses, and/or time periods. Data trends and projections will be contextualized both within and across hospitalizations, patient life spans, and/or varying patient populations. Context-based clinical decision support systems can alert for early recognition of conditions and greater implementation of evidence-based therapies.

Data science and AI algorithms integrated into the electronic health record and assisted by real-time point-of-care testing will aid in rapid medical diagnostics, identify patients at high risk for acute deterioration or development of complications, and guide personalized treatment. The algorithms that accomplish these feats will use secure technology to identify and track a patient's risk for decompensation, organ-specific injury (e.g., renal failure), intervention-specific complications or side effects (e.g., pneumothorax), guideline adherence, and clinical trial eligibility. It may also explain emergent events in real time. Data models will provide possible avenues of action, including potential effects on trajectories and recommendations to mitigate risks with subtle nudges to optimize delivery of patient-, clinician-, and unit-level quality measures. This will occur while integrating patient/caregiver preferences.

AI algorithms already exist to better recognize early signs of organ dysfunction, speech and vocal biomarkers indicative of dyspnea, asthma exacerbation, cognitive impairment, and high risk for clinical deterioration (11, 12). Still, in the future, data acquisition technology will be automated to provide more personalized, real-time prevention and treatment recommendations. AI algorithms using closed-loop iterative models will enable minute-to-minute titration of organ support treatments, such as continuous renal replacement, infusion pumps, mechanical ventilators, perfusion circuits, nutritional support, and pain or sedation support (13). Such technologies are currently in their infancy but, with enhanced algorithms, they will become more reliable, accurate, and able to promote better patient outcomes.

On a population level, better data acquisition and large-scale data analysis for patients with similar conditions located across disparate geographical sites will enable hospitals to evolve into true learning healthcare systems (14, 15). These systems will combine patient data, clinician-specific data and competencies, and healthcare system data including staffing, patient census, and supply availability to optimize healthcare delivery and improve equity. This can occur only when large-scale data across different institutions and healthcare systems can be securely combined into a single identity-protected mega-dataset for widespread use (16, 17). Such large-scale federation of patient, clinician, and healthcare system data will refine practices in different environments and help detect and mitigate disparities in healthcare delivery. Practice variations both within and across healthcare settings will be captured and analyzed to inform potential new areas of therapy and intervention (18). Indeed, one consequence of the COVID-19 pandemic has been the rapid adoption of international, multiplatform, adaptive, pragmatic clinical trials (19, 20). These large, federated international datasets will constitute an influential platform for clinical research design and integration. These datasets will allow for global pathogen surveillance and better detection of emerging pandemics. They will improve emergency responses to mass casualty events, natural disasters, and military conflicts and enable minute-by-minute awareness of situation severity as well as more efficient and equitable resource allocation across local, regional, and national healthcare agencies (21).

Challenges related to innovations in data acquisition include the need for rigorous and transparent safeguarding of patient privacy and ensuring equitable use of data, devices, and technology. During the next years to decades, patients, family members, clinicians, medical researchers, administrators, health policy advocates, and government and regulatory entities will need to partner together to demand and develop better transparency and assurance around data security, privacy, and sharing to protect patient health and well-being (22, 23). Current financial and banking practices already share such data with medical data requiring similar, if not even higher, security. Emerging strategies using blockchain technology have demonstrated that it is possible to federate data in ways that address security concerns (24). Yet as the use of such data increases, we must also demand that novel technologies be used equitably. Such potentially transcendent technology could alleviate disparities but could just as easily exacerbate them, particularly if technology and expertise are concentrated in institutions that are already well resourced rather than that in resource-limited environments that could benefit most (25).

THE CASE CONTINUES

Throughout the patient's hospitalization, her current and past records are seamlessly linked and available in an accessible format to all clinicians in real time and across the spectrum of hospital care settings and teams. Past discussions with other clinicians concerning her values and goals of care are available, allowing her current clinical team to meet her stated wishes and continue these discussions as needed. Although her multiprofessional care team may change as she is transferred in and out of the ICU, team members effectively communicate with each other throughout. The patient and her family and friends are considered part of her care team, and her family and friends can learn about and assist in her clinical care, if they wish. Devices in the patient's room allow her to see and interact with geographically distant family members and her spiritual leader. She and her family also use these devices to speak with other patients and support groups, receive information about her condition, communicate with her care team, view her current therapies, play music, and display images of her choosing. Bed motion and position sensors report a dashboard of patient activity, including the percentage of time the head of bed is less than 30%, the last time she was turned, agitation episodes, sleep quality, and ambient light and noise levels that conflict with her natural circadian rhythms. Sedative pharmacotherapy is less frequently needed because it has been increasingly replaced with technology that mitigates delirium development by engaging with the patient through conversation, games, massage, reading, ICU diary entry, orientation, and oral intake, as appropriate.

The patient recovers from her pneumonia and is extubated. Before discharge, a post-ICU clinic visit is arranged to help her continue her recovery beyond the ICU. Hospitalization records, with pertinent information related to potential ICU-related morbidities, are accessed electronically by her PCP and her other outpatient clinicians. She is discharged home with

wearable monitors for prediction and early detection of myocardial ischemia, sepsis, and other conditions that may occur after acute, severe pneumonia.

TOWARD A MORE PATIENT-CENTERED CRITICAL CARE TEAM AND ENVIRONMENT

The critical care team of the future will continue to be multiprofessional, with diverse generalists, therapists, specialists, and subspecialists seamlessly collaborating toward the common goal of optimal and humanistic patient care in a learning healthcare system (**Table 1**). The team's wearable technology will optimize staffing patterns by tracking and mitigating excessive workloads while monitoring for mental and physical fatigue and distraction that could worsen patient care and/or exacerbate clinician burnout (26). In addition to multiprofessional diversity, critical care teams of the future will also readily reflect the cultural, ethnic, gender identity, and geographic diversity of the communities

TABLE 1.
ICU Team of the Future Functioning Within a Learning Healthcare System

Workplace Challenges for the ICU Team		
Complex Patients	**Complex Environment**	**Complex Therapies**
Complex chronic comorbidities	Increasing technology	Closed-loop titration systems
Chronic invasive devices	Expanding documentation	Inflammatory response manipulation
Out-of-hospital monitoring	Risk of information overload	Stress response modulation
Compromised immune status	Challenges of continuity	Maintaining patient participation
Bimodal extended life span	Danger of alarm fatigue	Monitoring expected trajectory
Increased illness severity	Ensuring adequate handoff	New therapies to minimize postintensive care syndrome
	Telehealth from the ICU	Addressing patient, family, and clinicians
	Diurnal rhythm	
	Workforce shortages	
	Rising cost of healthcare	
Intercalated Elements of a Learning Healthcare System		
Patient Care	**Shared Education**	**Clinical Research**
Multidisciplinary	Just-in-time simulation	Links to national databases
Patient- and family-centered	Frequent debriefing sessions	Continuous QI
Evidence-based	Joint case reviews	All patients potential research subjects
Ultrasonography proficiency	Burnout risk awareness	Dashboards for QI activity
Holistic and humanistic	Monitoring of provider competency	
Characteristics of the ICU Team of the Future		
Individual	**Team**	**Administration**
Enjoys out-of-box challenges	Promotes situational awareness	Provides adequate staffing
Nurtures resilience	Encourages team members	Supports multifaceted QI
Engages in nonwork renewal	Encourages family as part of ICU team	Seeks suggestions for improvement
Values humanism in care	Avoids wasteful practices	Maintains awareness of front line
Practices personal wellness	Practices cross-training	Monitors staff turnover
Has ICU personality	Has multiprofessional and collaborative members	Facilitates/funds national networking
	Provides patient and family support and comfort	Offers lifestyle improvement perks

QI = quality improvement.

they serve (27) and be trained and skilled in communication approaches that are both patient- and family-centered as well as culturally competent and sensitive (28). Patients' families and friends will be further integrated into the ICU team and actively encouraged to participate in patient care (29). Geographically distant family members will be able to virtually follow the patient's course and communicate with the clinical team in real time and via messaging. Family and friends can provide specific information of what a restorative environment might consist of for the patient (e.g., family photographs, a personal diary, and nature imagery) (30) and help to emotionally support the patient and care team throughout the hospitalization.

Telehealth technology will be leveraged to facilitate ready consultation and communication with geographically distant specialists and subspecialists (31–33). Therapists from diverse disciplines (e.g., respiratory, occupational, physical, cognitive, and rehabilitation) will collaborate with critical care clinicians to develop and enact therapeutic plans that may start in the ICU and continue to outpatient and home-based settings (34, 35). Pharmacists will provide medication consultation throughout hospitalization. Dietitians will use patient-specific nutritional data from technologies such as indirect calorimetry, ultrasound, or MRI-evaluated muscles mass to inform individualized nutrition care plans (36). Critically ill patients who are cognizant but unable to verbalize will use technology-assisted devices to communicate (37).

The ICU environment of the future will be designed to support the physical, emotional, and spiritual needs of patients and family members and mitigate their risks for postintensive care syndrome (PICS), PICS-family, and PICS-pediatric (38–40). Wearable technologies and home-based rehabilitation programs will also better identify and ameliorate these syndromes (41). Future ICU design will distinguish between clinical and nonclinical areas to better integrate humanistic objects; the optimal setting will optimize physical, emotional, and mental well-being for the patient, family, and critical care team (42). Equipment and medical devices will be smaller and less obtrusive. The ICU bed will likely be able to draw specimens for laboratory tests, perform diagnostic imaging, and receive and administer medications. The bed may look like a full-body device that is worn, providing constant passive movement to ensure

muscles tone. (43) Critical care in the future may not be limited to a physical hospital location; ancillary critical care environments will potentially include a patient's home, field hospitals, or low-resource environments with virtual input from experts around the world (44, 45).

EMERGING TECHNOLOGY ADOPTION, EQUITY, AND THE ROLE OF PROFESSIONAL SOCIETIES IN THE FUTURE

Through advocacy, policy, and education, patients, families, clinicians, public health officials, government entities, and professional societies will need to drive innovation and change and to identify and mitigate barriers to critical care progress as well as critical care disparities (**Table 2**). Indeed, thoughtful and strategic alliances among diverse stakeholders will be essential for effective and equitable dissemination of evidence-informed critical care innovations.

As rapid evolution of technology will change the practice of critical care, it will also transform the ways professional societies support critical care practitioners and communities (**Table 3**). Critical care has always been a technology- and data-dependent field. As big data and technology potentially revolutionize critical care practice, professional societies are well positioned to partner with patients, families, practitioners, researchers, industry leaders, policymakers, and administrators to ensure that humanistic, high-value, ever-improving patient care remains the central goal for the future of critical care medicine.

CONCLUSIONS

It is not a futuristic concept to build a multiprofessional patient-centered critical care team that provides the right care to the right patient at the right time through the entire continuum of acute illness and injury. This is a timeless core principle of critical care medicine and comprises the "Right Care, Right Now" motto for the Society of Critical Care Medicine. What will change in the future is how we use data, devices, and new technologies to continue to strive toward that goal. These anticipated changes will occur throughout healthcare, though critical care may be at the forefront because of its data-heavy, complex environment and high-acuity, time-sensitive interventions. It is also

TABLE 2.
Overcoming Barriers

Domain	Approaches to barrier mitigation
Enhance collaboration and communication	Professional societies, government entities, public health officials, critical care clinicians, and patients and their families will need to come together to drive change and innovation to promote the optimal health outcomes of all. Communication and collaboration will be essential in creating the ideal future
Evolving technologies	All technologies and algorithms will need to be constantly, iteratively, and systematically evaluated for accuracy, validity, false alerts, and potential ingrained gender, racial, and/or socioeconomic biases
	Critical care practitioners, patients, and their families will also need to embrace a more integral role in the development, testing, validation, and implementation of technology and emerging artificial intelligence models to ensure that the models are useful, useable, enhance the value of care, and improve patient and family outcomes and experiences
Enhanced security of health data	Security features will need to evolve to protect health-related data; this is imperative to protecting against potential collapse of healthcare systems or, more importantly, unnecessary patient demise (22, 23)
Evolving research techniques	Well-designed randomized clinical trials will need to unequivocally demonstrate that novel algorithms and technologies effectively and equitably improve clinically relevant and patient-centered outcomes
Provider responsibilities to improve patient care	Critical care professionals will need to be open to adopting and implementing novel and emerging technologies, particularly when evidence supports that such technologies likely improve patient care and/or outcomes
	Equally important, professionals will need to reject or deescalate emerging technologies and processes when evidence indicates lack of benefit or potentially worse outcomes
Innovative educational models	Training of critical care professionals will need to include education on application of new technology and data science and interpretation of data and outputs of smart algorithms

our belief that critical care medicine practitioners are uniquely positioned to advocate for and lead the development and implementation of these future efforts to ensure that patient-centered care and patient, family, and clinician experience remain the central focus.

For more information on the Society of Critical Care Medicine Future of Critical Care Task Force timeline, process, and discussion topics, please see **Appendix A**, http://links.lww.com/CCX/A947, and **Appendix B**, http://links.lww.com/CCX/A948.

TABLE 3.
Role of Professional Societies in the Future

Domain	Approaches
Improve outcomes for a diverse population of critically ill and injured patients	Potentiate critical care research both through research funding portfolios and by enhancing knowledge dissemination
	Develop real-time updates to clinical practice guidelines
	Advocate for equitable and inclusive critical care, particularly in underresourced care settings
Expand and support a global network of critical care professionals	Develop collaborative relationships between and across local and global clinician organizations and critical care professionals
	Facilitate better development of practical and innovative tele-critical care networks
	Advance multimodal educational opportunities for diverse healthcare professionals
Advocate for patients, families, and critical care professionals	Partner with governmental entities, private foundations, nonprofit organizations, associations, industry, and other groups to better advocate for critically ill patients, their families, and their critical care practitioners
	Build and support innovative programs that potentiate thriving of critical illness survivors and their families
	Lead in public communications promoting critical care awareness

1   Emory Critical Care Center, Emory Healthcare, Atlanta, GA.

2   Division of Critical Care Medicine, Department of Medicine, Montefiore Health System, Albert Einstein College of Medicine, Bronx, NY.

3   Division of Pulmonary Medicine, Department of Epidemiology and Population Health, Montefiore Health System, Albert Einstein College of Medicine, Bronx, NY.

4   Division of Pulmonary, Allergy, and Critical Care Medicine, Department of Medicine, Duke University, Durham, NC.

5   Departments of Medicine and Anesthesiology, Seattle Children's Hospital, Harborview Medical Center, University of Washington School of Medicine, Seattle, WA.

6   Department of Biology, School of Biological Sciences, University of Utah, Salt Lake City, UT.

7   University of Pittsburgh, School of Pharmacy, Pittsburgh, PA.

8   New York Presbyterian Hospital, New York, NY.

9   Department of Emergency Medicine, Durham VA Medical Center, Durham, NC.

10 Intermountain Medical Center, University of Utah, Salt Lake City, UT.

11 Nutrition and Food Services, Wellstar Health System, Marietta, GA.

12 Department of Pharmacy, Beth Israel Deaconess Medical Center, Boston, MA.

13 Division of Trauma, Burns, Critical and Acute Care, Department of Surgery, Weill Cornell Medicine, New York, NY.

14 Department of Neurology, University of Virginia, Charlottsville, VA.

15 Center for Bioethics, Hennepin Healthcare, Minneapolis, MN.

16 Division of Pulmonary, Allergy, Critical Care and Sleep, Department of Medicine, Emory University School of Medicine, Atlanta, GA.

17 CommonSpirit Health, Tacoma, WA.

18 Department of Anesthesiology, Perioperative & Pain Medicine, Stanford University, Stanford, CA.

19 Division of Primary Care and Population Health, Department of Medicine, Palliative Care Section, Stanford University, Stanford, CA.

REFERENCES

1. Shankar-Hari M, Wunsch H, Rowan K, et al: Reflections on critical care's past, present, and future. *Crit Care Med* 2021; 49:1855–1865

2. Weil MH, Tang W: From intensive care to critical care medicine: A historical perspective. *Am J Respir Crit Care Med* 2011; 183:1451–1453

3. Weil MH, Shoemaker WC: Pioneering contributions of Peter Safar to intensive care and the founding of the Society of Critical Care Medicine. *Crit Care Med* 2004; 32:S8–S10

4. Annane D, Bellissant E, Bollaert PE, et al: Corticosteroids for treating sepsis in children and adults. *Cochrane Database Syst Rev* 2019; 12:CD002243

5. Jaeschke R, Angus DC: Living with uncertainty in the intensive care unit: Should patients with sepsis be treated with steroids? *JAMA* 2009; 301:2388–2390

6. Herasevich V, Litell J, Pickering B: Electronic medical records and mHealth anytime, anywhere. *Biomed Instrum Technol* 2012; Suppl:45–48

7. Schoettler N, Strek ME: Recent advances in severe asthma: From phenotypes to personalized medicine. *Chest* 2020; 157:516–528

8. Tsimberidou AM, Fountzilas E, Nikanjam M, et al: Review of precision cancer medicine: Evolution of the treatment paradigm. *Cancer Treat Rev* 2020; 86:102019

9. Wong HR, Atkinson SJ, Cvijanovich NZ, et al: Combining prognostic and shock responsive to corticosteroids. *Crit Care Med* 2016; 44:e1000–e1003

10. Weir CR, Nebeker JR. Critical issues in an electronic documentation system. *AMIA Annu Symp Proc.* 2007; 2007:786–790

11. Fagherazzi G, Fischer A, Ismael M, et al: Voice for health: The use of vocal biomarkers from research to clinical practice. *Digit Biomark* 2021; 5:78–88

12. Churpek MM, Yuen TC, Winslow C, et al: Multicenter development and validation of a risk stratification tool for ward patients. *Am J Respir Crit Care Med* 2014; 190:649–655

13. Branson RD: Automation of mechanical ventilation. *Crit Care Clin* 2018; 34:383–394

14. Morris AH, Stagg B, Lanspa M, et al: Enabling a learning healthcare system with automated computer protocols that produce replicable and personalized clinician actions. *J Am Med Inform Assoc* 2021; 28:1330–1344

15. Casey JD, Courtright KR, Rice TW, et al: What can a learning healthcare system teach us about improving outcomes? *Curr Opin Crit Care* 2021; 27:527–536

16. Estiri H, Klann JG, Weiler SR, et al: A federated EHR network data completeness tracking system. *J Am Med Inform Assoc* 2019; 26:637–645

17. Stephens KA, Anderson N, Lin CP, et al: Implementing partnership-driven clinical federated electronic health record data sharing networks. *Int J Med Inform* 2016; 93:26–33

18. Stoto M, Oakes M, Stuart E, et al: Analytical methods for a learning health system: 2. Design of observational studies. *EGEMS (Wash DC)* 2017; 5:29

19. REMAP-CAP Investigators; ACTIV-4a Investigators; ATTACC Investigators, Goligher EC, Bradbury CA, McVerry BJ, et al: Therapeutic anticoagulation with heparin in critically ill patients with Covid-19. *N Engl J Med*. 2021; 385:777–789

20. ATTACC Investigators; ACTIV-4a Investigators; REMAP-CAP Investigators; Lawler PR, Goligher EC, Berger JS, et al: Therapeutic anticoagulation with heparin in noncritically ill patients with Covid-19. *N Engl J Med*. 2021; 385:790–802

21. Walsh DP, Ma TF, Ip HS, et al: Artificial intelligence and avian influenza: Using machine learning to enhance active surveillance for avian influenza viruses. *Transbound Emerg Dis* 2019; 66:2537–2545

22. Sabin S: Hospital ransomware attacks now have deadly consequences. Politico. October 4, 2021. Available at: https://www.politico.com/newsletters/weekly-cybersecurity/2021/10/04/hospital-ransomware-attacks-now-have-deadly-consequences-798002. Accessed November 4, 2021

23. Storm D: MEDJACK: Hackers hijacking medical devices to create backdoors in hospital networks. Computerworld. June 8, 2015. Available at: https://www.computerworld.com/article/2932371/medjack-hackers-hijacking-medical-devices-to-create-backdoors-in-hospital-networks.html. Accessed November 4, 2021

24. Warnat-Herresthal S, Schultze H, Shastry KL, et al; COVID-19 Aachen Study (COVAS); Deutsche COVID-19 Omics Initiative (DeCOI): Swarm learning for decentralized and confidential clinical machine learning. *Nature* 2021; 594:265–270

25. Tossas-Milligan KY, Winn RA: Breaking the cycle of health inequities: The bioethics of data. *J Health Care Poor Underserved* 2019; 30:86–90

26. Rosen MA, Dietz AS, Lee N, et al: Sensor-based measurement of critical care nursing workload: Unobtrusive measures of nursing activity complement traditional task and patient level indicators of workload to predict perceived exertion. *PLoS One* 2018; 13:e0204819

27. Sprung CL, Jennerich AL, Joynt GM, et al: The influence of geography, religion, religiosity and institutional factors on worldwide end-of-life care for the critically ill: The WELPICUS study. *J Palliat Care* 2021 Apr 5. [online ahead of print]

28. Markin A, Cabrera-Fernandez DF, Bajoka RM, et al: Impact of a simulation-based communication workshop on resident preparedness for end-of-life communication in the intensive care unit. *Crit Care Res Pract* 2015; 2015:534879

29. Wyskiel RM, Chang BH, Alday AA, et al: Towards expanding the acute care team: Learning how to involve families in care processes. *Fam Syst Health* 2015; 33:242–249

30. Nadkarni NM: After the fall: The tapestry of disturbance and recovery. *Crit Care Med* 2017; 45:348–355

31. Subramanian S, Pamplin JC, Hravnak M, et al: Tele-critical care: An update from the Society of Critical Care Medicine Tele-ICU Committee. *Crit Care Med* 2020; 48:553–561

32. Fathi JT, Modin HE, Scott JD. Nurses advancing telehealth services in the era of healthcare reform. *Online J Issues Nurs*. 2017; 22:2

33. Davidson R, Barrett DI, Rixon L, et al; ACT Program: How the integration of telehealth and coordinated care approaches impact health care service organization structure and ethos: Mixed methods study. *JMIR Nurs* 2020; 3:e20282

34. Nicholls J, MacKenzie C, Braund R: Preventing drug-related adverse events following hospital discharge: The role of the pharmacist. *Integr Pharm Res Pract* 2017; 6:61–69

35. Kirkham HS, Clark BL, Paynter J, et al: The effect of a collaborative pharmacist-hospital care transition program on the likelihood of 30-day readmission. *Am J Health Syst Pharm* 2014; 71:739–745

36. Looijaard WGPM, Molinger J, Weijs PJM: Measuring and monitoring lean body mass in critical illness. *Curr Opin Crit Care* 2018; 24:241–247

37. Wilkinson KM, O'Neill Zimmerman T, Light J: Visual attention to cued targets in simulated aided augmentative and alternative communication displays for individuals with intellectual and developmental disabilities. *J Speech Lang Hear Res* 2021; 64:1726–1738

38. Mikkelsen ME, Still M, Anderson BJ, et al: Society of Critical Care Medicine's international consensus conference on prediction and identification of long-term impairments after critical illness. *Crit Care Med* 2020; 48:1670–1679

39. Needham DM, Davidson J, Cohen H, et al: Improving long-term outcomes after discharge from intensive care unit: Report from a stakeholders' conference. *Crit Care Med* 2012; 40:502–509

40. Manning JC, Pinto NP, Rennick JE, et al: Conceptualizing post intensive care syndrome in children-the PICS-p framework. *Pediatr Crit Care Med* 2018; 19:298–300

41. Major ME, Dettling-Ihnenfeldt D, Ramaekers SPJ, et al: Feasibility of a home-based interdisciplinary rehabilitation program for patients with post-intensive care syndrome: The REACH study. *Crit Care* 2021; 25:279

42. Kesecioglu J. Improving the patient's environment: The ideal intensive care unit. *Réanimation* 2015; 24:341–343

43. Halpern NA, Anderson DC, Kesecioglu J: ICU design in 2050: Looking into the crystal ball! *Intensive Care Med* 2017; 43:690–692

44. Sessler CN: Evolution of ICU design: Smarter is better. *Chest* 2014; 145:205–206

45. Amaral AC, Rubenfeld GD: The future of critical care. *Curr Opin Crit Care* 2009; 15:308–313