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Adopting Technological Innovations to Enhance Disaster Event Response

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Abstract

The convergence of medical and technological developments has continued to transform the delivery of medical care in disaster environments, incorporating advances from telecommunications to physiologic monitoring, artificial intelligence, and computer vision. However, unless the interconnected nature of these developments is conceptualized with a proper framework, there is a risk of overlooking applications, developing silos, and limiting interoperability between innovations. To develop such a framework, this piece integrated a review of current literature, expert insights, and global market trends to propose 4 categories of innovations: (1) Enabling Technologies, (2) Signal Acquisition, (3) Data Utilization, and (4) Applications. Applications can be further subdivided into 4 use cases: (1) Disease and Injury Surveillance and Detection, (2) Population Protection, (3) Responder Protection, and (4) Disease and Injury Management. Practitioners, policymakers, and private sector counterparts can utilize this framework to change their clinical practices, allocate funds in a stepwise fashion, or prioritize development projects, respectively.

Concurrent revolutions in biology and technology are converging to transform the way that medical care is provided in complex environments, from future battlefields to rural hospitals. Groundbreaking advances in telecommunications, physiologic scanning, biosensing, and the expanding applications of artificial intelligence, machine learning, and computer vision have all coalesced to produce unique solutions in the operational emergency medical domain. Examples of technological utilities in these settings include remote patient monitoring, real-time telehealth consults, drone deliveries of medical supplies, and more.[1] However, there remains a major challenge in organizing how these technological solutions are researched, developed, funded, and applied. Because they are often created without collaborative planning, they ignore the potential for broader application, frequently lack interoperability, and are often pursued without a clear basis for prioritization. This paper presents a conceptual framework for how these intersecting advances in medicine and technology should be developed, adopted, and iterated upon.

To develop a framework for conceptualizing intersecting advances in medicine and technology, the authors reviewed peer-reviewed and gray literature regarding new technologies in health care assessment and delivery. They also examined advances described in the disaster medicine literature concerning the adoption of new technologies in support of event response. Relevant information was extracted and categorized. To complement this literature scan, the authors held numerous informal conversations on innovation with relevant experts. Information from the literature review and interviews were analyzed alongside global market trends in emergency health technology capabilities to develop the proposed framework. The collective insights comprising the framework illustrate both where technologies can be most useful and examines how they build upon each other in a pyramidal fashion. Iterations of this concept have been further refined after a presentation in May 2023 at the World Association of Disaster and Emergency Medicine.[2]

Discussion

Technological innovations for response to disaster events, both sudden in onset (e.g., earthquakes) as well as those that develop over time but are sustained because of prevailing conditions (e.g., hurricanes, pandemic response), can be categorized into 4 broad categories: (1) enabling technologies, (2) signal acquisition, (3) data utilization, and (4) applications. Figure 1 illustrates these 4 categories in ascending order, with definitions as follows.

Enabling Technologies

Enabling technologies are those that improve network infrastructure and data communication, forming the foundational layer upon which other technologies are reliant. These developments

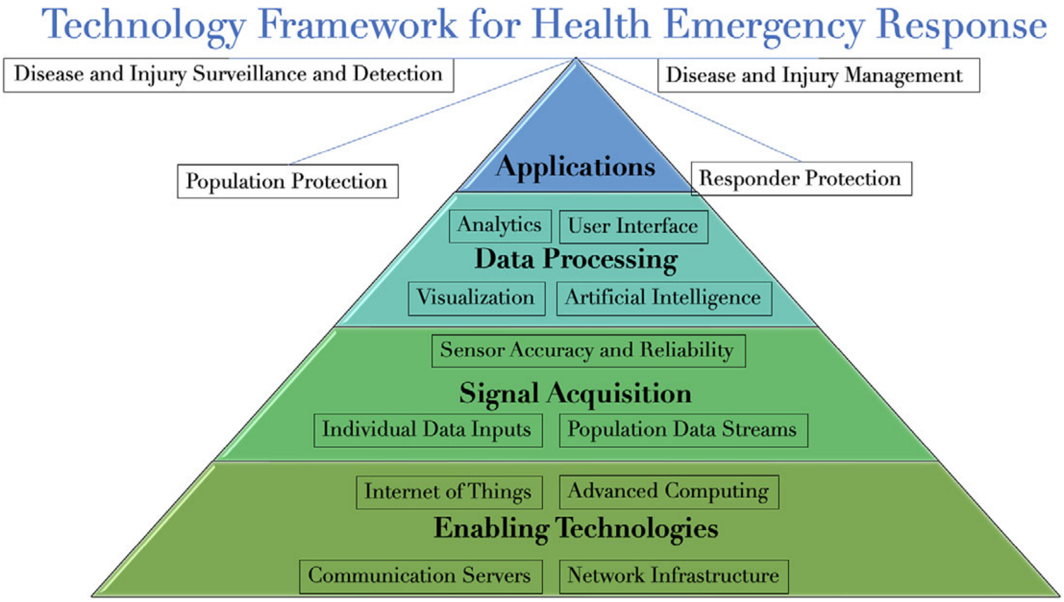

Figure 1. Pyramidal Technology Framework for Health Emergency Response.

are not necessarily created to advance medicine but have immense utility in the medical sphere. Examples of enabling technologies include the advent of 5G broadband cellular networks, which have utility for general consumer communications but can now facilitate the connectivity of remote devices used in medical evaluation and care. With its dramatically higher bandwidth, or quantity of information that can be transmitted, and lower latency, or transmission time, 5G can send information that can be used for real-time medical decision-making.[3] Furthermore, advances in satellite technology to utilize 5G could extend this high bandwidth, low latency capability into disaster environments when local communication towers are disrupted.[4]

Beyond communication across distant locations, technology improvements have also locally supported connection through the Internet of Things (IoT), which refers to the network of interconnected devices and sensors that extends computing capability to items not traditionally considered computers.[5] Of specific relevance is the Medical Internet of Things (mIOT), which simply applies the IoT concept in environments where the devices and sensors are medical.[6]

Another critical enabling technology is advanced computing, which encompasses innovations that expand the data processing power of computers to rapidly process increasingly large amounts of information.[7] Given the massive amount of data submitted into medical records and captured by medical monitoring, advanced computing can generate actionable insights from patient information to inform clinical and public health decisions when minutes could make a difference in mortality.

The related concept of edge computing is also a core enabling technology that focuses on decentralizing computing power to devices rather than requiring processing by a central computer system.[8] Empowering devices to have computational capability means extending their ability to perform desired functions when communication is limited, which could be the case in disaster settings. While this is not always feasible, the authors view this functionality as a key criterion in the selection of new technologies deployed for operational emergency medicine and disaster response functions. Still another enabling technology would be blockchain, homomorphic encryption, or distributed ledger technology, which has gained public popularity for its role in cryptocurrency and financial transactions but could be utilized in medicine to enhance data privacy and security or facilitate medical record exchange.[9,10] The use of haptics represents another enabling technology with relevance to medicine as it delivers cutaneous and kinesthetic sensations that can align a sense of touch with feedback from a remote location.[11] The commonality across each of these enabling technologies is that they are being developed as broader tools for a variety of commercial applications now being considered for their use in the field of medicine.

Signal Acquisition and Scaling

As the foundational capability to transmit large quantities of data very quickly between remote locations develops, it is also crucial to ensure that the data's quality and utility are maximized. Signal acquisition is the layer of this architecture that focuses on these capabilities, covering not only the accuracy of the signal, but also the practicality, durability, size, and form factor of the acquisition systems, as well as the identification and development of new signals to capture.

One subset of signal acquisition includes biological signals that can be measured individually. This includes vital signs like body temperature, blood pressure, pulse, breathing rate, and blood oxygen content, but could also extend into other autonomic nervous system signals being studied in the field of bioelectronic medicine.[12] Additionally, superficial measurement of electrical activity enables acquisition techniques like electromyography (EMG), electroencephalography (EEG), galvanic skin response (GSR), and others.[13] Platform biological assays, such as multi-omics, will help elucidate the intra-person variability of complex biological systems. As sensors improve, they may support new ways to measure these biological signals, alongside uncovering new biological signals to capture. Beyond physical measurements, signal acquisition could also come in the form of improved visual and auditory information.

On a population level, signal acquisition includes scaling these signals to understand inter-person variability over time and large-scale inputs like wastewater collection, which has shown effectiveness in predicting hospitalizations and Intensive Care Unit (ICU) admissions during outbreaks like the COVID-19 pandemic. By innovating to uncover more accurate population-level data collection approaches, or discovering new types of data sources about populations, signal acquisition at scale can set the stage for large-scale analysis, prediction, and response in the setting of disasters or pandemics.

Data Processing

With the right data in hand, the next phase of technological innovation comes into play: data processing. This includes the processing and transformation of raw data, the analysis of these data, the creation of visualizations for these data, and the further display of these data in user interfaces that are most useful for providers or responders as they support patients or decision-makers who require situational awareness. Supported technologies that play a role at this level include those that utilize artificial intelligence (AI) solutions like machine learning (ML), deep learning (DL), natural language processing (NLP), and computer vision (CV).[14]

Applications

Finally, the integration of enabling technologies, signal acquisition, and data processing translates into useful applications, which are complete systems that can be utilized to prevent disease through preparedness and response activities and improve clinical care for patients in crisis settings. Because disaster events are inherently chaotic, and often result in the loss of critical infrastructure, including the very communications architecture that so much of the relevant technologies rely upon, any adoption of technologies to support disaster response must accommodate for such contingencies. What follows is a description of key applications that would be useful in sudden onset or sustained disaster events. These are categorized based on the core capabilities inherent in any response: (1) Disease and Injury Surveillance and Detection, (2) Population Protection, (3) Responder Protection, and (4) Disease and Injury Management, as seen in Figure 2.

Disease and Injury Surveillance and Detection

The first category encompasses technologies that help characterize the onset, scope, scale, and severity of a sudden or slowly evolving disaster event utilizing a network of wearable devices, physiological sensors, and remote disease sampling tools. The broadening adoption and use of commercial-grade tools including fitness watches demonstrate the potential utility of physiological monitors applied across a population. These devices have been of particular interest during the COVID-19 pandemic, with numerous studies taking place across the country,[15], [16,17] while others have speculated about the utility of such wearables for monitoring the health of astronauts[18] or soldiers on the battlefield.[19] Some studies have even shown promise in detecting illness up to 6 days before disease onset.[20] For remote wearers during an earthquake or regionally located users at the start of a pandemic, predictive monitoring can be useful in determining when a change from homeostasis has occurred and when medical intervention on an individual scale or population health readiness on a large scale may be necessary. Additional surveillance applications beyond wearable biomarkers may include wastewater surveillance to geographically and temporally predict disease spread[21,22,23] or cough detection[24] to identify increased frequency of illness or even specific types of illnesses in public spaces.

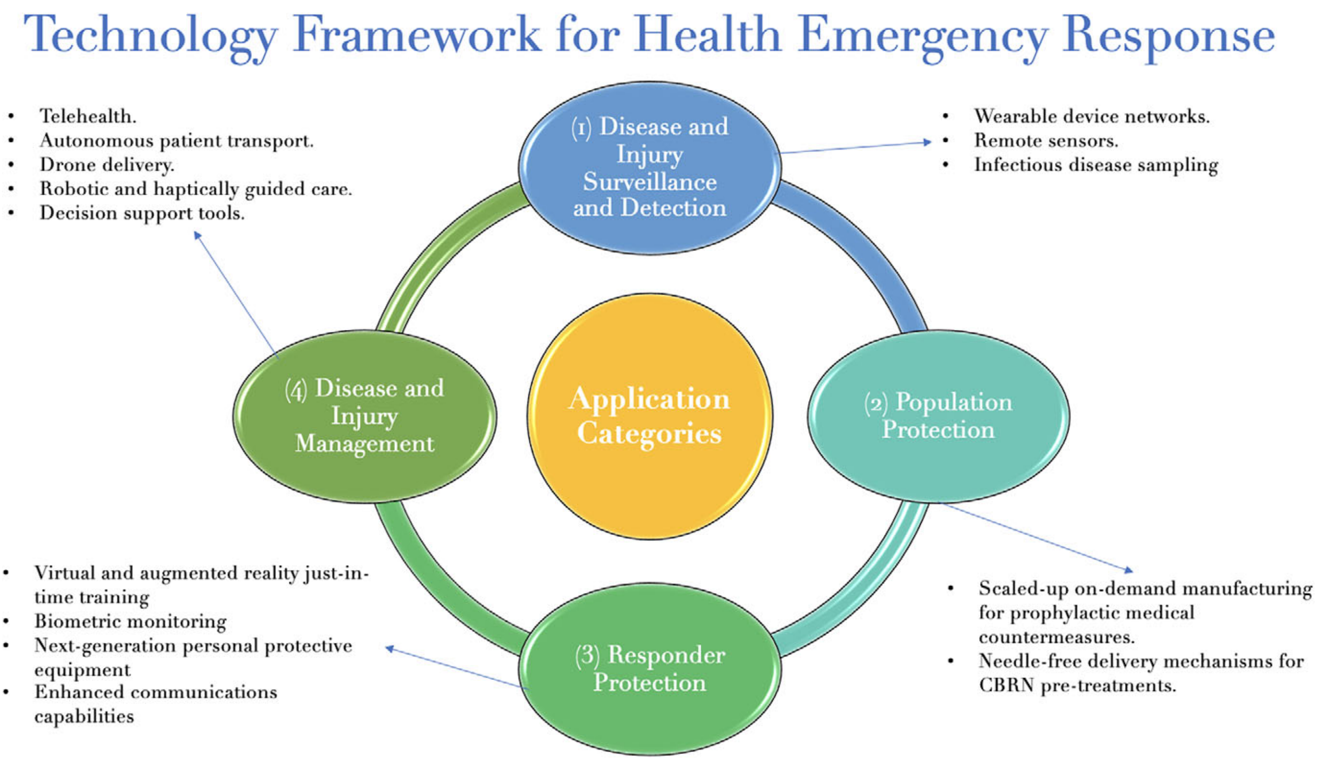

Figure 2. Application Categories for Health Emergency Response.

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While widespread data collection may help with disease surveillance, it can also strengthen algorithms to offer prognostic analyses about which patients are likely to survive mass casualty events. Underlying each of these applications remain the enabling technologies like developments in the healthcare Internet of Things, within which these independent technologies are brought together in a cohesive network to perform in concert.[25]

Population Protection

Scaling response activities to the population level requires identifying and characterizing subpopulations at risk for adverse health outcomes, often by aggregating results of surveillance activities, and determining the extent to which the risks affect these individuals. This information influences both near- and long-term resource decision-making, as well as operational planning, logistics support, and access to care.

In the immediate aftermath of an event, affected individuals require care with resources brought into the affected zone. This could include the onsite production of countermeasures or lab materials to address barriers to transporting supplies from afar, including through the use of 3D printing[26,27] or the conversion of waste products like ditch water into blood products.[28,29] Innovative delivery mechanisms could even be used to deploy these onsite production technologies into combat or disaster scenarios, transporting drug-producing machines, trauma-assistive care systems, and advanced surgical supplies to the point of injury. The automated delivery of medical supplies to responders by drones is already being pursued by small companies that have worked to deliver drugs, vaccines, and blood supplies to remote areas or disaster zones using drones, and by corporate giants that have partnered to deliver prescriptions to retirees.[30,31]

Throughout this phase of response, remote monitoring of patients and resource levels could ensure that logistical resupply is optimized to where it is most needed and situational awareness is maintained across both the public and decision-makers. Here, at least some knowledge of past disaster response events, who was affected, and why, combined with data from the current response, enables evaluation of these data. The application of advanced analytics, such as forecasting models and scenario planning models, can facilitate strategic and operational readiness, particularly for prolonged responses, as well as inform health policy decisions.[32,33] These models require several enablers discussed above, such as advanced computing and the development of field-forward decision science tools for local response efforts that can draw inferences from broader, unrelated disaster health events.

Responder Protection

There will be no effective operational response to a disaster event without considering the steps needed to ensure responder protection. Health care and emergency responders require additional support before, during, and following an incident response. Such efforts can be facilitated by just-in-time training and clinical decision support with simulations, virtual reality, and augmented reality, applying biometric monitoring or *in vivo* sensors to look for changes in responder physiology, and adoption of next-generation personal protective equipment or innovations that let responders assist remotely.

Before a crisis or shortly after one has occurred, just-in-time training to scale the volume of responding personnel and simulation technologies will be helpful in training responders to deal with the circumstances they will face, from triage decision-making to procedures like field limb amputations or cricothyrotomies. For disaster environments in particular, virtual reality may assist expeditionary medical teams with desensitizing personnel to the traumas, training teams that are not geographically co-located, and maintaining psychomotor skills during lull periods where skills may otherwise atrophy.[34,35] These tools will also be relevant during the response when telemedical consultation can enable on-the-ground responders to be advised by remote experts. Rather than splitting attention between a patient and a telemedical conferee, augmented reality goggles may provide decision support and feed information from remote providers directly into a responder's field of vision. Such a tool has already been pursued by the US Army, which developed a lightweight set of goggles that provides a digital display of information to complement a soldier's normal vision.[36,37] When paired up with portable handheld tools, including portable point-of-care ultrasound systems, these goggles reduce cognitive load and save valuable time, as well as space, in a provider's bag.[38]

Providers may also get a helping hand from systems that automatically capture health information, populate electronic health records with such data, and utilize artificial intelligence (AI) to provide decision support after drawing conclusions from large swaths of data. Such systems may save time and ease the cognitive load for providers while also ensuring that full documentation is covered, enabling more thorough research studies, predictive analyses, and casualty reviews to take place. Further applications of the same monitors and analyses described above, supported by advances in enabling technologies like network infrastructure and computer miniaturization, could aid providers in tracking patient status post-diagnosis and moving providers out of dangerous areas. The same monitoring used for patients could also be used to evaluate the health and well-being of responders, triggering alerts when responders are injured or if they show signs of acute distress and burnout.

Disease and Injury Management

The distribution of necessary medical resources to patients in need and the safe evacuation of patients, as well as those unaffected by the disaster event, may be constrained - especially in the setting of sudden-onset disasters. Once such an incident occurs, technologies aimed at Disease and Injury Management are necessary to preserve the well-being of citizens. First, affected and unaffected populations need to be identified. With the widespread utilization of tools like wearable devices, IoMT interconnectedness, and strong satellite connectivity to maintain data transfer in the event of cell tower blackouts, signals could be rapidly processed to sort injured from uninjured personnel. After, the injured personnel could be triaged to determine who needs immediate intervention before or during an evacuation, while those who are unaffected could be targeted for communication about evacuation and health preservation steps.

Once sick and healthy patients have been sorted, new technologies can be implemented to assist with evacuation. Autonomous or remotely controlled vehicles could be applied to maximize evacuation capacity with available staff or to minimize risk to responders. As expected, these devices would be dependent on their own set of enabling technologies, signal acquisition sensors, and data processing tools.

Delivering care to patients in health care emergencies will require optimized allocation of scarce resources based on disease or injury acuity and survivability. Effective health care service delivery can be bolstered using telehealth, autonomous patient

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transport, drone delivery, robotic and haptically guided care delivery, and decision support tools. The most straightforward innovation that has taken hold in recent years is that of telemedicine, or the use of technologies to remotely diagnose, monitor, and treat patients.[39] Telemedicine can be either asynchronous, involving messages sent and responded to at different times, or synchronous, involving concurrent visual and auditory communication.[40] While primary care, behavioral health, critical care, and numerous specialty appointments may all be useful in normal times, this technology may be particularly valuable during times of crisis. For example, by the end of March 2020 alone, telehealth appointments had increased 152% compared with the same period in 2019 due to the COVID-19 pandemic serving as a forcing factor.[41]

The existence of tele-critical care for burn, stroke, and critical care patients is transforming conventional medical care already, but the generation of telemedical programs for combat and disaster casualty care provides an expanded use for telemedical programs.[42] The US military's Telemedicine & Advanced Technology Research Center, or TATRC, is leading the way in transforming connectivity in combat or disaster environments. The Center notes that normal demand for telemedicine in combat is 70% asynchronous and 30% synchronous in ways involving critical care, surgical support, or teleconsultation. However, in mass casualty settings, the division is inverted, causing synchronous surgical and critical care support to become dominant.[43] Bolstering teleconsultation and procedural capabilities are enabling technologies in the connectivity space like 5G technology, which makes high-quality video conferencing to remote locations and real-time remote monitoring even more feasible.[44]

While telehealth consultations and technology-assisted care may supplement the local provider's efforts with remote medical expertise, what if this heightened connectivity could even let providers perform operations out of harm's way? Advances in surgery, for example, have led to the da Vinci system, which allows surgeons to operate on patients through an in-room technological system and arguably performs better than humans,[45] and competitors like Vicarious Surgical are working to extend the distance between patient and provider even further.[46] A portable version of such remote surgical systems could allow for damage control surgery to take place in remote or dangerous environments with minimized threats to providers. Such capabilities may also allow for routine or emergency surgeries to continue while local providers are preoccupied with caring for disaster-affected patients. Surgeries can even be done in rural clinics that cannot afford to employ specialist surgeons or fail to recruit them due to geographical preferences, though purchasing relevant technologies might be an additional financial hurdle to consider.[47] These applications will be reliant on improvements in the enabling technology of haptic feedback, which can provide real-time sensory feedback for a remote surgeon.[48]

Furthermore, as algorithms improve, AI processing of scans may help create rapid and accurate diagnoses. For example, AI may help with identifying pneumothorax, intracranial hemorrhage, and pulmonary embolism on scans without the clinician needing to pause their care to read them.[49,50] This will also allow for lifesaving diagnoses to be made in the field by a larger number of providers, not all of whom will need to be trained to the level of physician, physician assistant, or nurse provider. Furthermore, new evaluative tools like a handheld tool to diagnose infectious disease or cardiovascular illnesses through a patient's breath are being studied by the Air Force and the National Aeronautics and Space Administration (NASA).[51] Each of these technologies relies not just on the higher-level application, but the incremental, foundational developments in data acquisition and processing that came before them.

New automated technologies may also come in handy to assist providers in the mechanical provision of care, like devices that assist providers by automatically assessing Endotracheal Tube placement based on chest X-ray images.[52] Even staples of combat casualty care like tourniquets may be improved with AI and pressure transducers, enabling automated tourniquet application and incorporating microseconds of release to stimulate collateral blood flow as needed.[53,54]

It is essential to note that these applications can overlap across categories. For example, remote surgical technologies can both protect responders by letting them operate from safe distances and improve patient care by bringing in surgical expertise from afar that would otherwise be unavailable. Furthermore, advanced clinical decision support tools will reduce provider fatigue and sift through information overload while optimizing care for patients. Additionally, these applications might build upon numerous levels of the pyramid in Figure 1; applications might combine enabling technologies of advanced sensors, edge computing, and internet-of-things with deep learning algorithms to detect symptoms and offer medical decision support to providers.[55]

Theoretical Case Study: Utility in an Earthquake Response

Figure 3 illustrates the application of this theoretical framework to an earthquake. The foundational enabling technologies of relevance to the earthquake response would be the utilization of a joint disaster electronic health records integration system to collect patient information from different international providers or organizations centrally, particularly when it can integrate data from an IoT network of devices. In turn, this would require strengthened satellite communication platforms to facilitate communication and data gathering in the absence of ground-level infrastructure. At the signal acquisition level, portable and durable biometric monitors that can be applied to patients, or even visually assess vital signs and injury, would be critical, while dashboard monitoring of resources could provide a data source for supply monitoring. For the data utilization level, dashboard tools to display the amount of selected medical supplies throughout different areas of the city could help with resource allocation and hospital load-balancing tuned to meet patient care demand, and simultaneous biometric displays of entrapped patients could help providers monitor patients whose rescues are underway. At the top of the pyramidal framework, the relevant application technologies include algorithmic triage based on pooled biometric data from patients, drone resupply of medical supplies in the areas identified through the supply visualization tools, and real-time video consultation devices to get remote input from orthopedists and vascular surgeons. This earthquake example serves to illustrate how technologies can build upon each other to enable use cases relevant to all forms of disasters.

Limitations

This framework seeks to broadly categorize technologies into levels and application types to assist with prioritizing technology and transfer efforts and increasing interoperability, but its scope does not cover the regulatory challenges at places like the Food and Drug Administration (FDA) or the licensure and reimbursement requirements of various jurisdictions.[56,57] These advances are pushing into uncharted territory, where the infrastructure for evaluating

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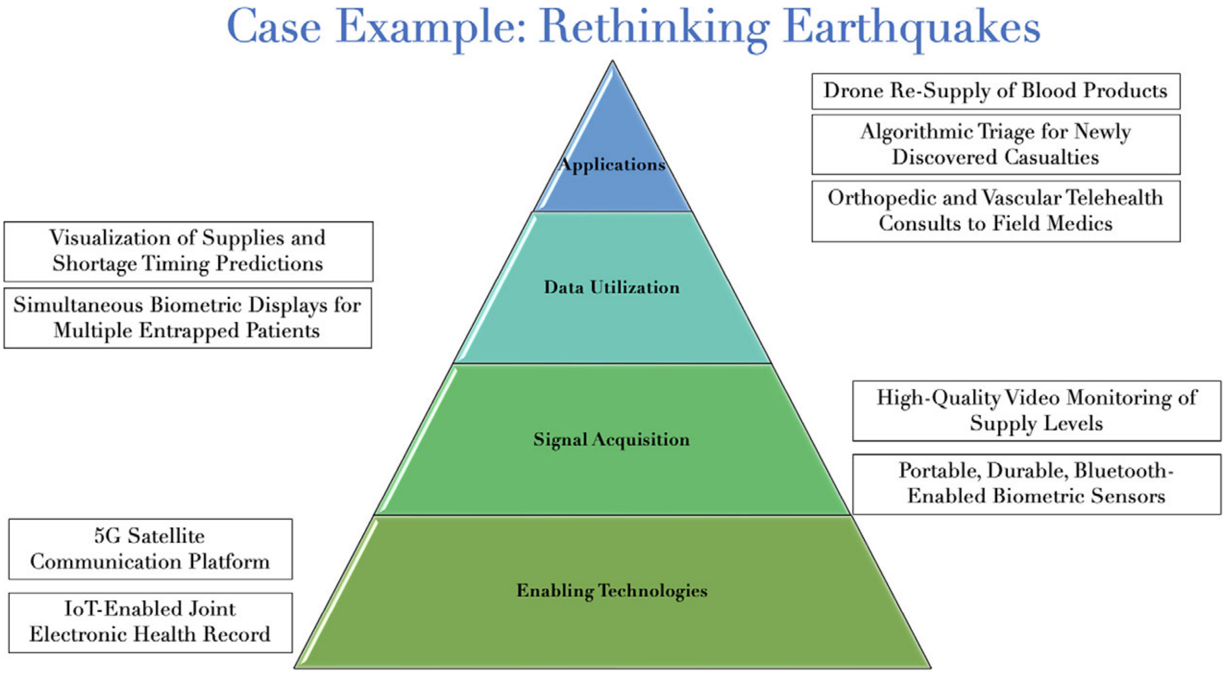

Figure 3. Theoretical Case Study Using an Earthquake Response.

efficacy and safety is underdeveloped, so appropriate regulatory and reimbursement considerations should be integrated when decision-makers are allocating funds or provider groups are prioritizing. Questions of cybersecurity and ethics must also be addressed for any technologies powered by autonomous robotics and AI algorithms to ensure that human oversight is appropriately integrated.

Furthermore, while this framework intends to reduce siloes, it is predicated on widespread reach and communication, which must extend beyond the efforts funded by the government to reach private sector and non-government sectors as well. Bringing diverse stakeholders to the table to share their requirements, discuss potential solutions, and collaborate in their development is a crucially important part of turning futuristic visions into reality. This inclusivity further prevents the duplication of efforts and avoids losing track of projects that are developed independently, a problem that the Pentagon is currently trying to reconcile.[58] When projects are tracked and managed successfully, they can also be prioritized as needed and viewed as interdependent.[59] This will further ensure standardization and integration exist across initiatives to minimize the cost and effort of training end-users.

Conclusion

As innovations in both technology and biology rapidly progress, various stakeholders must understand how to prioritize and integrate these changes. For practitioners of emergency, pre-hospital, and disaster medicine, this means considering the use cases and being open to changing their clinical and public health practice. For policymakers, this means allocating research and development funds in a stepwise fashion, funding enabling technologies at high levels while adjusting data utilization and application funds accordingly. For the private sector, this means focusing efforts on those categories that can be rapidly advanced for the benefit of patients and providers. Overall, effectively managing the successful adoption and implementation of the innovative tools described above requires the comprehensive categorization of their areas of impact and utility. This framework guides emergency managers, policymakers, and private sector innovators alike to understand how individual developments coalesce in the larger context of disaster prevention, response, and recovery.

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