Received: 7 May 2024 | Revised: 11 June 2024 | Accepted: 14 June 2024

DOI: 10.1002/joa3.13103

CLINICAL REVIEW

Journal of Arrhythmia Open Access WILEY

Addressing out-of-hospital cardiac arrest with current technology advances: Breaking the deadlock with a mobile network

Meiso Hayashi MD, PhD[1,2] | Yu-ki Iwasaki MD, PhD[2]

[1]Humanities and Social Sciences 2, College of Arts and Sciences, The University of Tokyo, Tokyo, Japan

[2]Department of Cardiovascular Medicine, Nippon Medical School, Tokyo, Japan

Correspondence
Meiso Hayashi, Department of Cardiovascular Medicine, Nippon Medical School, 1-1-5 Sendagi, Bunkyo-ku, Tokyo, Japan.
Email: m-h4510@nms.ac.jp

Abstract

Out-of-hospital cardiac arrest (OHCA) is a global public health problem, with survival rates remaining low at around 10% or less despite widespread cardiopulmonary resuscitation (CPR) training and availability of automated external defibrillators (AEDs). This is partly due to the challenges of knowing when and where a sudden OHCA occurs and where the nearest AED is located. In response, countries around the world have begun to use network technology-based smartphone applications. These applications are activated by emergency medical service dispatchers and alert preregistered volunteer first responders (VFRs) to nearby OHCAs using Global Positioning System localization. Accumulating evidence, although mostly from observational studies, shows their effectiveness in increasing the rate of bystander CPR, defibrillation, and patient survival. Current guidelines recommend the use of these VFR alerting systems, and the results of ongoing randomized trials are awaited for further dissemination. This article also proposed the concept of a life-saving mobile network (LMN), which uses opportunistic network and wireless sensor network technologies to create a dynamic mesh network of potential victims, rescuers, and defibrillators. The LMN works by detecting a fatal arrhythmia with a wearable sensor device, localizing the victim and the nearest AED with nearby smartphones, and notifying VFRs through peer-to-peer communication. While there are challenges and limitations to implementing the LMN in society, this innovative network technology would reduce the tragedy of sudden cardiac death from OHCA.

KEYWORDS
alerting application, first responder, mobile network, out-of-hospital cardiac arrest, sudden cardiac death

1 | INTRODUCTION

Out-of-hospital cardiac arrest (OHCA) is a life-threatening event that requires urgent response, most of which occurs unexpectedly in individuals who have never been reported to have heart abnormalities.[1] It has been a major public health problem worldwide, accounting for 15%–20% of all deaths[2] and affecting nearly 350 000; 80 000; and 46 000 people annually in the United States,[3] Japan,[4] and France,[5] respectively. Although regional differences in the incidence of OHCA have been reported,[6] with Asia having a lower rate of emergency medical service (EMS) attended OHCA compared with Europe, North America, and Australia, recent statistics[7] have revealed the relatively high incidence of EMS-assessed OHCA in China (95.7 per 100000 person-years), suggesting that the management of OHCA is an important issue worldwide. These epidemiological data also suggest the need for more comprehensive measures to prevent sudden cardiac death, including the way of addressing sudden OHCA once it occurs.

Despite more than a quarter of a century of cardiopulmonary resuscitation (CPR) training and widespread deployment of automated external defibrillators (AEDs), the overall survival rate for OHCA patients remains quite low, at around 10% or less worldwide,[3,4,5,7,8] but we believe that there is scope for technological innovation to address these issues. This article focuses on increasing the rate and speed of initiation of bystander CPR with defibrillation using portable electronic devices (primarily individual smartphones). The text is divided into three main sections. The first is the current state of OHCA and CPR. The second is a new context for CPR using smartphone applications, which has developed rapidly over the past decade. Finally, we propose a new methodology using an ad hoc peer-to-peer network connecting individual electronic sensors and devices to further reduce the number of missed sudden OHCA patients. We hope that the methodology proposed in this review, with further refinement and development by the readers of this article, will mitigate the tragedy of sudden cardiac death.

2 | THE IMPORTANCE OF EARLY CPR WITH DEFIBRILLATION

Out-of-hospital cardiac arrest is caused by rapid and sustained, circular, or spiral electrical activity called ventricular tachycardia (VT) or ventricular fibrillation (VF), which turns well-synchronized regular heart contractions[9] into convulsive movement, resulting in a loss of cardiac output and blood flow to the brain and heart itself; this fatal arrhythmia causes victims to lose consciousness in seven seconds[10] and die after 10min.[11,12] Such arrhythmias causing OHCA is rare in people under the age of 35 and are usually associated with inherited arrhythmias and cardiomyopathies.[2,13] The incidence of OHCA increases rapidly after the age of 60, with the majority of cases due to coronary artery disease (Figure 1).

Irrespective of underlying heart disease, it is crucial to initiate CPR in VT/VF immediately after checking for unconsciousness and abnormal breathing (a pulse check is not necessary for lay rescuers).[3,14] Basic life support (BLS) consists of chest compressions to the lower sternum to a depth of 5cm at a rate of 100–120/min and two consecutive rescue breaths for every 30 compressions.[3] Without CPR, survival from fatal arrhythmias decreases by approximately 7% to 10% per minute,[11,12] and the current average time for EMS to arrive after a call in the United States[15] and Japan[4] is approximately 7 and 9min, respectively. In addition, although bystander CPR certainly increases the rate of survival by two- to three-fold,[4,16,17] BLS itself does not maintain sufficient blood flow to keep victims alive for long. Its effectiveness is maximized by the simultaneous use of a defibrillator to terminate VT/VF. Defibrillation before EMS arrives is the key to saving sudden OHCA victims.[18-20]

Unfortunately, current CPR statistics are disappointing. For example, according to the latest official report from the Japanese Ministry of Internal Affairs and Communications, which represents statistics for the whole of Japan in 2022,[4] even among the victims whose collapse was fortunately witnessed by others, 1-month survival was confirmed in only 10.3% of the cases, whereas bystander CPR doubled the survival rate and the use of AEDs before the arrival of EMS was highly effective with a survival rate of 50.3% (Figure 2). The reason for such a low overall survival rate in these statistics is considered to be the insufficient participation rate of CPR (59.2%) and the desperately low rate of AED use (4.3%) even in these witnessed cases, and these are also common problems worldwide.[3,4,8,19,21,22,23]

Strategic placement of AEDs may increase bystander defibrillation rates. From the early days of commercialization to the present, various studies have been conducted to determine where AEDs are most efficiently placed.[24-26] In the early period, AEDs were installed in high-traffic public places such as airports and casinos.[27,28] Subsequently, spatial analysis[25] and further examination considering temporal coverage found that AEDs were more likely to be used in locations that were easily visible 24h a day, such as coffee shops and bank ATMs.[26] Although such an efficiency perspective is valuable, the number of patients that can be saved by this measure alone would be insufficient. On a national level in the United States, 30 million AEDs are estimated to be needed to cover 70% of the population in nonresidential, urbanized areas. The estimated number of AEDs, however, sold since the 1990s is 4.5 million as of 2019.[29] In Japan, which is said to have the second largest number of AEDs after the United States, there were about 670000 AEDs in operation as of 2022,[30] but its utilization rate is still quite low.[4]

Survival rates decrease by 10% for every 100m between the location of the cardiac arrest and the AED.[31] Even if an incident fortunately occurs within 100m, there is still the issue of recognizing an AED.[32] For example, in a survey of the general public in the United Kingdom, only 5% knew where and how to find the nearest AED, and only 2% would actually retrieve and use it in a cardiac arrest situation.[33] Although, public education, including training in schools, is important,[34,35] new tools to support bystander rescuers who are willing to rush to the scene and equipped with CPR skills are obviously needed.

3 | MOBILE DEVICE APPLICATION TO CROWDSOURCE RESUSCITATION FOR SUDDEN OHCA

Various strategies are currently being proposed and implemented to address the problem of low bystander CPR rates and underutilization of AEDs. One area that has rapidly gained prominence over the

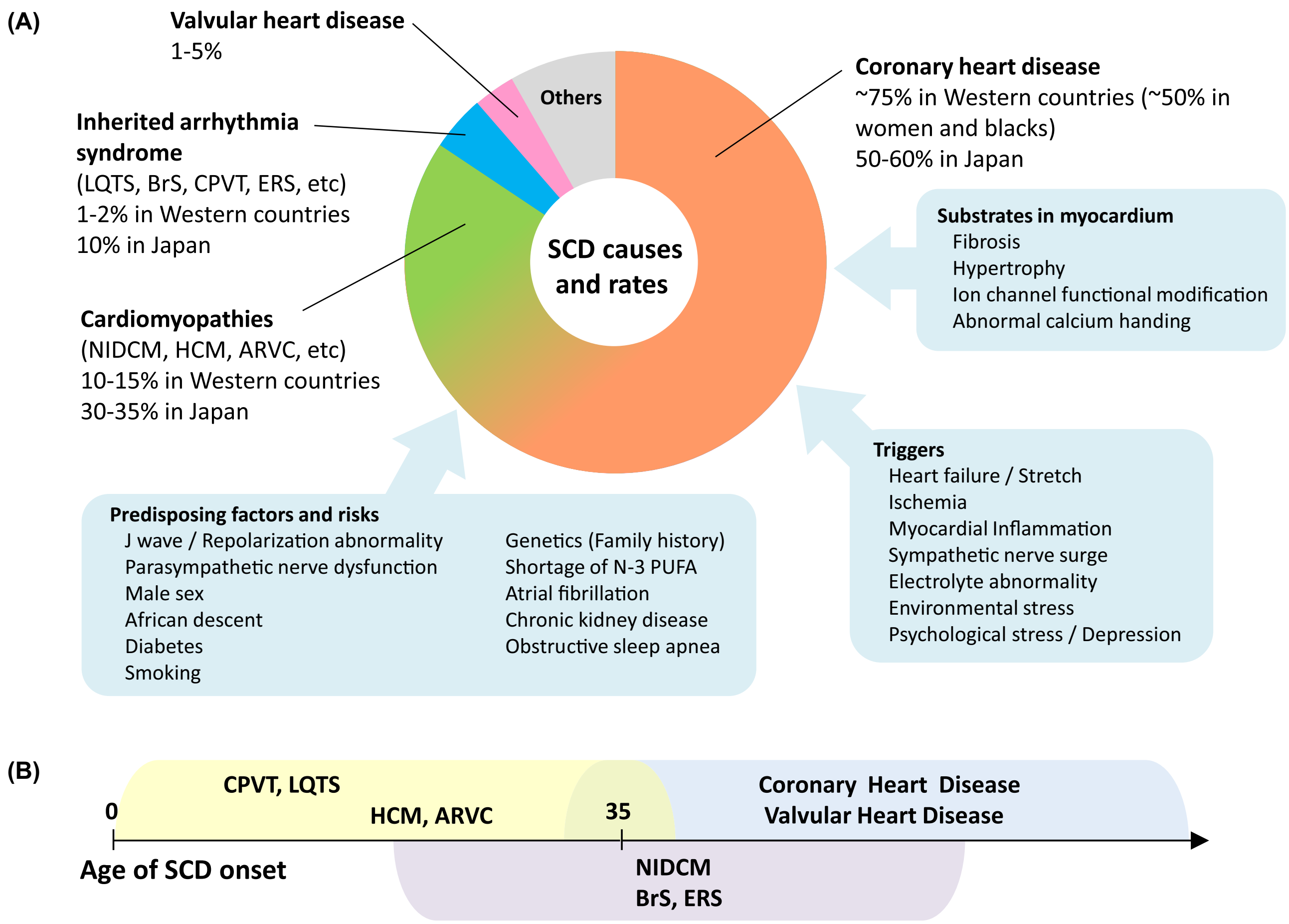

FIGURE 1 Causes of sudden cardiac death (SCD) from out-of-hospital cardiac arrest and rates (A) and age of onset of SCD in each disease (B). ARVC, arrhythmogenic right ventricular cardiomyopathy; BrS, Brugada syndrome; CPVT, catecholaminergic polymorphic ventricular tachycardia; ERS, early repolarization syndrome; HCM, hypertrophic cardiomyopathy; LQTS, and long-QT syndrome; NIDCM, non-ischemic dilated cardiomyopathy; PUFA, polyunsaturated fatty acids. Cited from Hayashi et al.[2] with permission.

last decade is the use of personal electrical devices. As of 2022, the cumulative number of mobile smartphone subscriptions worldwide have reached 6.4 billion.[36] These devices can be used not only to find the location of nearby AEDs with digital mapping software but also to receive emergency alerts from EMS about a nearby OHCA via text message or applications.

The system of sending texts from the EMS to neighboring citizens in the event of an OHCA to facilitate voluntary CPR has been in place in Switzerland since 2006,[37] and the work of Ringh et al.[38,39] in Sweden has stimulated this area of research. They developed a system in which the location of the OHCA and of preregistered volunteer first responders (VFRs) within 500 m of the location was automatically determined from emergency calls to the EMS dispatch center using a mobile phone positioning system through communicating base stations.[40] The system then sent text messages to the VFRs where the accident occurred. In the pilot study,[38] about half of the VFRs arrived at the scene before the EMS. In a trial reported in 2015,[39] investigating whether the system significantly increased the rate of bystander-initiated CPR, alerts to VFRs (9828 persons in Stockholm County with a population of 2 million) were randomly assigned. It was shown that in 81% of the intervention arm, at least one VFR was present within 500 m of the OHCA site, in 65%, one or more VFRs tried to reach the patient, and in 13%, CPR was initiated by the VFRs before anyone else arrived. Eventually, bystander-initiated CPR (including lay rescuers who were not preregistered VFRs) was performed in 62% of the intervention group and 48% of the control group ($p < .001$). On the other hand, there was no difference in return of spontaneous circulation (29.4% vs. 29.1%) or 30-day survival (11.2% vs. 8.6%), probably due to insufficient statistical power and the fact that the text message-based system was not integrated with an AED registry.

In Switzerland, in addition to the text message-based system used since 2006, a smartphone application with GPS system was introduced in 2014.[37] Prospective observational analysis showed that the application resulted in a significantly shorter arrival time (3.5 min vs. 5.6 min) and higher survivable discharge rates (28% vs. 17%) compared to text messages. Application-based systems are now the norm. A common feature of these applications is that they are linked to the EMS dispatch center. When a call suggests a sudden OHCA, preregistered VFRs in the vicinity are notified of the location

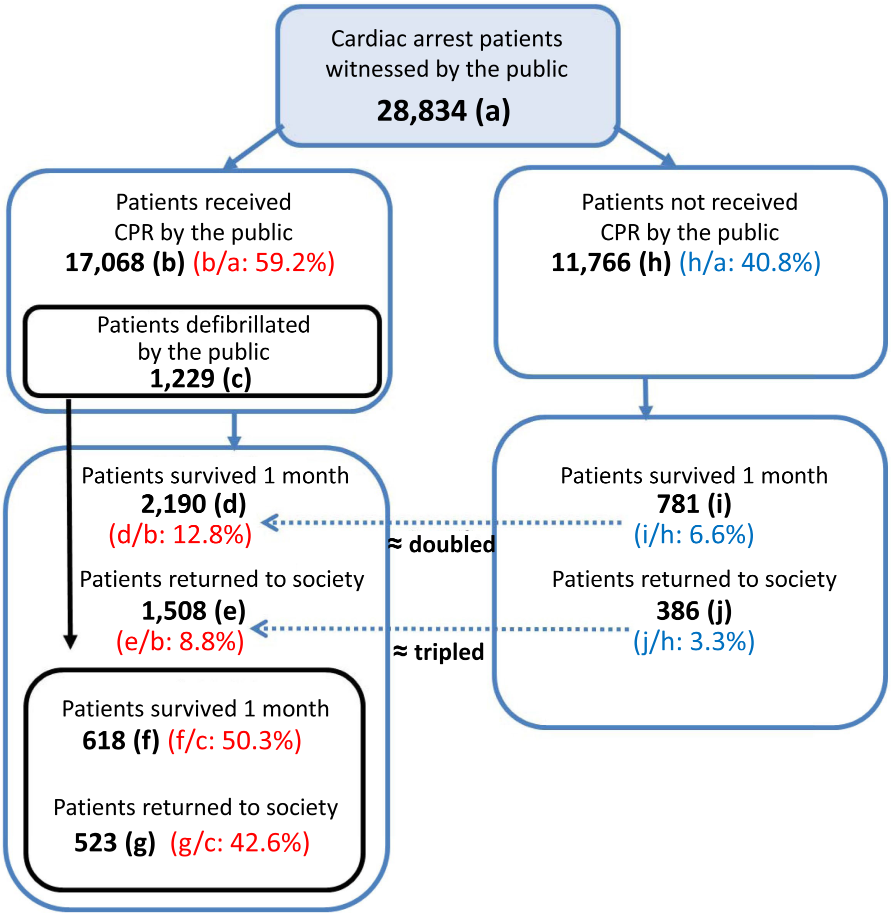

FIGURE 2 Prognosis of Japanese cardiac arrest patients witnessed by the public with and without cardiopulmonary resuscitation in 2022. Adapted and translated from Japanese into English from the official report of the Japanese Ministry of Internal Affairs and Communications[4] with permission.

and directions to the scene based on real-time GPS location information (Figure 3). Many applications also display the nearest AEDs, and there are also applications that split the notifications to direct VFRs to go to the scene or to retrieve AEDs. The maximum distance from the location of the OHCA to the citizen receiving the notification varies depending on the application, and the user receiving the notification can respond with acceptance or rejection. Table 1 shows the characteristics of representative smartphone applications in Europe, North America, and Japan.

Several studies have shown improvements in the time to the arrival of the first rescuer at the scene of an OHCA with these VFR alerting systems. In a prospective observational study in Germany,[41] the response time to the arrival of rescuers at the scene was significantly shorter for OHCAs with CPR initiated by a VFR compared with those initiated by EMS (median 4 vs. 7 min, $p<.001$). Similarly, in a retrospective study on a rural island in Denmark,[42] the median response time for all responding volunteers was 4:46 min:sec compared with 10:13 min:sec for EMS ($p<.0001$).

There is also some evidence that the VFR alerting system has reduced the time to AED attachment. In a prospective observational study[43] conducted in the Netherlands in 2014, volunteers who received a text message with the location of the OHCA were also shown the location of an AED within 1000 m of the patient. The median time from call to first AED shock for VFRs receiving the message was 8:00 min:sec (184 OHCAs), significantly shorter than 10:39 min:sec (739 OHCAs) for EMS ($p<.001$). In a subsequent report[44] that further expanded the number of cases, the time to first shock with any defibrillator was also reduced from 11.7 min before the introduction of the alerting system to 9.3 min after the introduction in residential areas (1201 OHCA), and also from 9.2 min before to 8.0 min after in public areas (542 OHCA).

4 | OUTCOMES OF SYSTEMS DISPATCHING VFRs TO OHCA SITES

Scquizzato et al.[45] conducted a meta-analysis of 10 articles (seven in Europe,[39,41,44,46,47,48,49] two in Asia,[50,51] and one in the United States[52]) published up to 2022 on text message- or application-based VFR alerting systems for OHCA. Compared with the standard EMS system, the VFR alerting system was associated with higher rates of patient survival at hospital discharge or 30 days (odds ratio

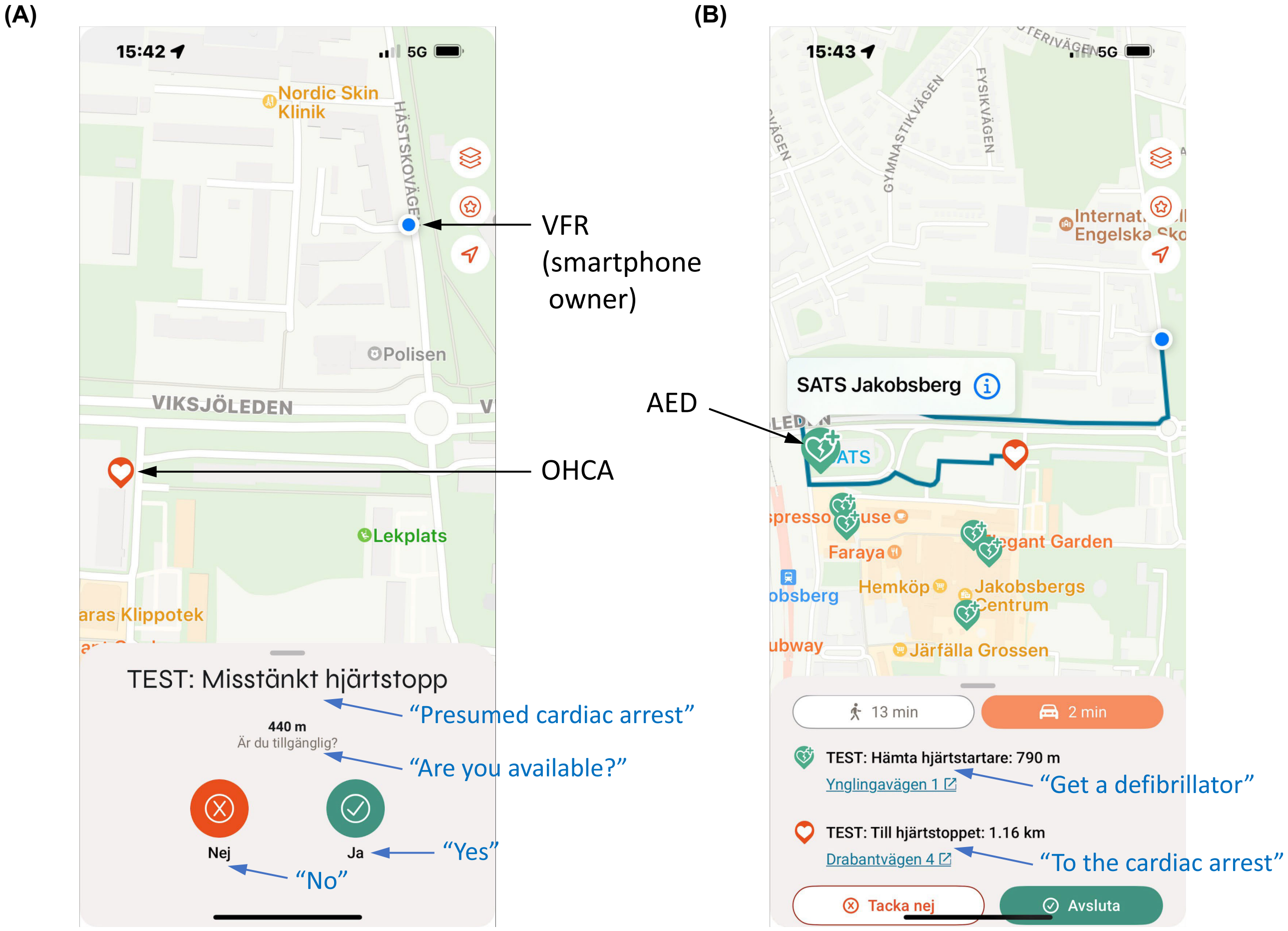

FIGURE 3 Smartphone screens of the HeartRunner application. When the emergency medical service dispatcher activates the system, the current locations of the out-of-hospital cardiac arrest (OHCA) and the preregistered volunteer first responder (VFR) are displayed on the VFR's smartphone (A). In this test case, they are 440 m apart. The alerted VFR taps whether they are available or not. If the VFR answers "Yes," a route is displayed on the map via the nearest automated external defibrillator (AED), the location of which is provided by the national Swedish AED Registry (B). Clicking on another AED on the map will change the route. The route also changes automatically based on the mode of transport (in this case a car) and whether or not the AED is to be retrieved.

[OR], 1.45; 95% confidence interval [CI], 1.21–1.74; $p<.001$). Rates of return of spontaneous circulation were higher in OHCAs with activation of the alerting system than in those with the standard EMS system (OR, 1.40; 95% CI, 1.07–1.81; $p=.01$). Rates of bystander-initiated CPR (OR, 1.75; 95% CI, 1.43–2.15; $p<.001$) and AED use before EMS arrival (OR, 1.82; 95% CI, 1.31–2.53; $p<.001$) were also significantly higher with the alerting system. These data are promising, but only one randomized trial[39] was included in this meta-analysis, and the certainty of evidence in other observational studies was very low according to the methodology used.[53]

A large registry study[54] was also published in 2023, which retrospectively analyzed data of the VFR alerting systems in five European regions: two in Sweden and one each in the Netherlands, Denmark, and Switzerland. Four regions used a system that employed an application with GPS-based localization, whereas one region used a system that sent text messages based on registered addresses. According to the pooled analysis, using a propensity score to adjust for differences between groups, OHCAs with activation of the VFR alert showed an increase in bystander CPR (risk ratio [RR], 1.30; 95% CI, 1.15–1.47; $p<.0001$), bystander defibrillation (RR, 1.89; 95% CI, 1.36–2.63; $p=.0001$), and 30-day survival (RR, 1.22; 95% CI, 1.07–1.39; $p=.0026$) compared with those without activation. These results corroborate those of previous meta-analyses,[45] but the observational measures of the study should be carefully considered. In OHCAs with activation of alerting system, the rate of shockable initial rhythms (24.9% vs. 18.1%, $p<.001$) was significantly higher than in those without, and this parameter was not included in the propensity score calculation because of concerns about introducing overadjustment bias.

Based on these data, the VFR alerting system can be considered a promising approach that has the potential to improve the prognosis of sudden OHCA patients. Current guidelines also recommend the use of these systems. The 2020 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations,[55] which summarizes the publications of the International Liaison Committee on

TABLE 1 Representative volunteer first responder applications in Europe, North America, and Japan.

	HeartRunner Sweden	HeartRunner Denmark	PulsePoint	AED GO
Launch year	2009[a]	2017	2011	2017
Available country	Sweden	Denmark	USA and Canada	Japan
Alert sender	EMS dispatcher	EMS dispatcher	EMS dispatcher	EMS dispatcher
Alert transmission radius (m)	Maximum 10000[b]	Maximum 5000[b]	400	1000
VFR localization method	GPS	GPS	GPS	GPS
No. of registered VFRs (n)	Over 140000[c]	Over 160000[c]	Over 1073000[c]	2860[d]
CPR training for VFR	Recommended but not mandatory	Recommended but not mandatory	Recommended but not mandatory	Varies by region
Max no. of VFR sent alert (n)	30	20	No limit	Varies by region
No. of registered AEDs (n)	24164[c]	25994[c]	Over 160000[c]	998[d]
Splitting VFRs to BLS and AED	Yes	Yes	No	No
Ref. no. in the present article	38, 39, 54, 61, 63	46, 54, 60, 61	52, 58, 59	Full paper not published

Abbreviations: AED, automated external defibrillator; BLS, basic life support; CPR, cardiopulmonary resuscitation; EMS, emergency medical system; GPS, global positioning system; USA, United States of America; VFR, volunteer first responder.

[a]Launch of the first system. The current system was introduced in 2015.

[b]The alert radius expands from the victim's location until it reaches the preset number of VFRs or the maximum radius selected.

[c]As of March 2024.

[d]As of April 2024.

Resuscitation (ILCOR), recommends that “citizens/individuals who are in close proximity to a suspected OHCA event and are willing to be engaged/notified by a smartphone application with a mobile positioning system or a text message-alert system should be notified (strong recommendation, very low-certainty evidence).” In line with ILCOR, the European Resuscitation Council Guidelines 2021[56] also made a similar strong recommendation, although with a “very-low-certainty evidence” provision. The 2020 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care[57] state that “The use of mobile phone technology by emergency dispatch systems to alert willing bystanders to nearby events that may require CPR or AED use is reasonable,” with a moderate (2a) class of recommendation and an evidence level B-NR, indicating moderate-quality evidence from one or more well-designed, well-executed nonrandomized studies or meta-analyses of such studies.

While all these guidelines recommend the use of the VFR application, they also point out the lack of evidence. In response, several randomized control trials are currently in progress. The HeartRunner Trial (ClinicalTrials.gov Identifier: NCT03835403), being conducted in Denmark, will assess patient survival in cases, where VFRs are activated via the Heartrunner application to retrieve an AED and go to the scene of suspected OHCA, compared to those who receive standard EMS care. Incoming calls to the EMS dispatch center are randomized 1:1 with and without activation of the VFR alerting system. The primary outcome is 30-day survival, and several secondary outcomes such as rates of bystander defibrillation, bystander CPR, and neurologically intact survival will also be compared. The study plans to enroll 1600 cases of OHCA and is expected to be completed in May 2026. The PulsePoint Study (ClinicalTrials.gov Identifier: NCT04806958) underwent in the United States will evaluate the effectiveness of the PulsePoint system compared to standard dispatch procedures in patients with OHCA. The primary outcome is the proportion of patients who receive bystander CPR or defibrillator use before EMS arrives. The proportion of patients surviving hospital discharge and those with a good functional outcome are the secondary outcomes. The sensitivity and false-positive rate of PulsePoint activation will also be evaluated. The estimated number of OHCA patients enrolled is 522 and the study is expected to be completed in March 2025. The results of these studies will add robust evidence to the debate on the efficacy of the VFR alert application, for which there has only been one RCT[39] to date, and may serve as a stimulus for further widespread adoption of the system.

5 | STATISTICS ON VFR ALERT APPLICATIONS

The acceptance rate of alerts on the application by preregistered VFRs is not very high, ranging from 23% to 30%.[46,47,58] A recent study[49] in the United Kingdom showed a particularly low rate of 16%, and following this study, the app was updated to allow alerts sound even when the smartphone was in silent mode. In addition, a study[59] in the United States reported that in 64% of all OHCA events, an unwalkable spatial area, such as terrain, water, road without a crosswalk, railroad, and private property, was observed within the alert transmission radius centered on the OHCA. This may partly explain the fact that, of those who accept the alert, 28%–40% do not actually arrive at the scene of the OHCA,[47,58] which makes the low acceptance rate even more worrying. Alerts are sent to multiple VFRs in the vicinity of OHCA patients, and several studies[39,48] have reported that the probability of at least one responder accepting the alert is greater than 65% per OHCA case. However, the OR of bystander defibrillation rises as the number of responders increases.[60] When one, two, and three or more responders were present before EMS arrived, the OR was 1.97 [95% CI, 1.12–3.52], 2.88 [95% CI, 1.48–5.58], and 3.85 [95% CI, 2.11–7.01], respectively. It is therefore desirable for more people to arrive at the scene. In addition, among OHCA cases in which alerts were issued, at least one VFR arrived at the scene before the EMS in 26%–42%,[46,61,62] and performed BLS in 13%–25%.[39,47,48] This proportion is expected to increase as more responders agree to the alert. To improve the acceptance of alerts by VFRs, efforts should be considered to increase the installation of the alerting application, to find the optimal radius and number of responders to send alerts, to improve the user interface and functionality of the application, and to increase incentives, such as sending letters of appreciation to participating volunteers.

Ideally, both the sensitivity and specificity of alerting should be high. Some studies[46,48,54] in which the EMS dispatcher decided whether to activate the VFR alerting system reported that of the OHCA cases where alerting was appropriate, alerts were actually issued in about half or less of the cases (39%–51%). Reasons for not issuing an alert include cases where there are no VFRs around the OHCA or, conversely, where the OHCA occurs in a crowded place such as a shopping mall or sports venue where bystander candidates and AEDs are already nearby,[48] which is understandable. On the other hand, a study[52] analyzing an alerting system that automatically triggers alerts based on EMS determinant codes entered into a computer-aided dispatch system found that only 7.6% of all dispatches resulted in an OHCA encounter. This rate was much lower than the 33%–56% of appropriate alerts among all alerts issued in similar systems.[39,46,47,62] These differences are probably due to the level of involvement of the EMS dispatcher in activating the alerting system. Automating the activation of alerts may speed up the dispatch of VFRs and reduce the burden on EMS dispatchers. However, if the specificity of the alerts is too low, it could cause physical and mental stress for the volunteers, and skepticism towards the alerts, so-called alert fatigue, could potentially lead to a decrease in their acceptance. Further research is also needed on the optimal criteria for activating the alerting system. The above and other improvements to the VFR alerting system are summarized in Figure 4.

6 | RETRIEVE THE AED OR GO DIRECTORY TO THE SCENE

The VFR alerting applications used in many communities can display AEDs located near the OHCA site on a map (Figure 3). As mentioned in an earlier section, activation of these systems can increase bystander defibrillation rates. However, it is difficult for the notified VFR to prioritize between AED retrieval and BLS, although some applications are able to send notifications to responders (Table 1), dividing them between those who retrieve the AED and those who go directly to the OHCA scene.[44,46,48] In promoting these systems, the question of what instructions to give to VFRs is important, and the results of a recently published randomized trial[63] have brought this back to the fore. In this study, VFRs receiving an OHCA alert were randomized into two groups: the intervention group, in which four out of five responders were instructed to retrieve the AED and the route to the AED was displayed on their smartphone, and the control group, in which all responders were instructed to go directly to the scene of the OHCA and the location of the AED was not displayed. The primary outcome of bystander AED attachment occurred in 13.2% of patients in the intervention arm compared to 9.5% in the control arm ($p = .08$). In this study, 24 of the 61 AEDs (39%) in the intervention arm were actually attached by VFRs, and 18 of the 46 AEDs (39%) in the control arm were also attached by VFRs. This suggests that crossover and low adherence to instructions prevented the verification of the issue. In the meantime, it is noteworthy that in both groups, almost 40% of all AEDs were attached by VFRs. This strongly suggests that the VFR alerting system can increase the rate of AED use.

A new initiative to have VFRs carry their own portable AED at all times is currently underway in France.[64] A randomized trial called The FIRST trial[65] is also being conducted in Australia and New Zealand to confirm the effectiveness of such efforts. In the trial, ultra-portable, fully automated AEDs that can be carried in a pocket are randomly assigned to high-frequency VFRs of the alerting application, defined as responders who have accepted at least three OHCA alerts in the past 3 years. The 30-day survival rate of OHCA patients will be compared between those treated with VFRs with and without the ultra-portable AEDs. In addition to evaluating the efficacy of having a subset of people carry AEDs at all times, this study can be the catalyst for the transition from the current static-AED era to the incoming mobile-AED era.

7 | ENGINEERING FOUNDATION FOR A SYSTEM TO SAVE LIVES FROM SUDDEN OHCA

At present, all mobile VFR alerting systems are activated only after someone happens to notice the event and makes an emergency call. We believe that to move to the next stage of eliminating sudden death from OHCA, patients should be identified and treated

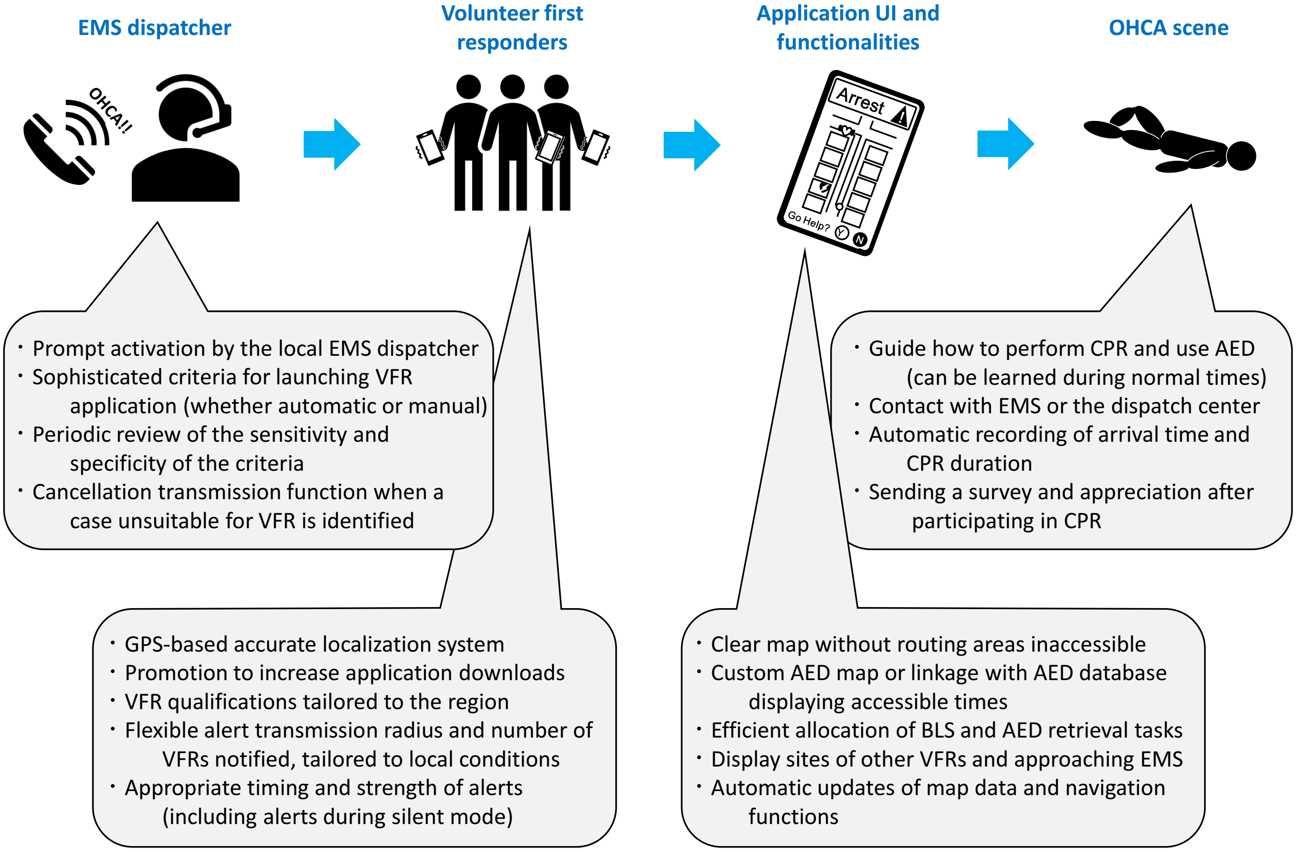

FIGURE 4 Factors for further increasing the sudden OHCA survival rate on the VFR alerting system. Enumerated improvements for the VFR alerting system at each stage, from the EMS dispatcher to the OHCA scene. AED, automated external defibrillator; CPR, cardiopulmonary resuscitation; EMS, emergency medical service; OHCA, out-of-hospital cardiac arrest; UI, user interface; VFR, volunteer first responder.

with AEDs much earlier after the onset of VT/VF and the current proliferation of smartphones[36] and tablet devices can be contributed to address these issues. A key structure is a mobile opportunistic network (OppNet)[66,67] and a wireless sensor network (WSN).[68,69]

The concept of OppNet has been proposed to deal with cases where the cellular network should be offloaded (i.e., some data traffic should be shifted to other networks, e.g., from the cellular network to Wi-Fi, to reduce network congestion), such as festivals and sports venues, or in areas with communication challenges where infrastructure is not available, such as disaster areas or sparsely populated regions.[66] It is an ad hoc (without prior planning) communication system involving a plurality of electrical devices or sensors called "nodes." Unlike a traditional infrastructure-based network with a star topology, where each device communicates with only one access point, this network has a dynamic mesh topology formed by nodes. Each node is directly and nonhierarchically connected to others, instantly and opportunistically forming a system that relays information (Figure 5). When a seed node (the most upstream in the network) sends a message, it is received by a nearby node, which stores the information in its buffer, and when a new communication opportunity arises, the message is forwarded to other nodes until it reaches its destination. In many cases, where nodes are not static but dynamic, such as smartphones or vehicles, the path of the message changes dynamically. OppNet is an evolving field with extensive research underway, and to accommodate its unique network environment, various routing protocols have been proposed for more efficient and economical information transfer.[67]

Wireless sensor network is another pillar of our proposal and has also been the subject of many vigorous research efforts in recent years. With the proliferation of various sensors used in the field, such as natural resource exploration, target tracking, unapproachable place monitoring, and the ubiquitous Internet of Things, WSNs that collect information from these sensors and control them have attracted considerable attention and cover a wide range of applications.[68,69] These sensors in the WSN are also called nodes. In traditional WSNs, these nodes are considered static, but as numerous sensors are embedded in mobile devices, WSNs including these devices are becoming more dynamic. In the operation of WSN, not only the collection and transmission of data but also the localization of sensor nodes is crucial for the optimal routing of information, and the methodology for this has been developed with increasing accuracy. The localization methods are categorized, such as anchor-based/free localization or GPS-based/free localization, etc.[70] "Anchor" nodes are a reference point used to calculate the position of other nodes

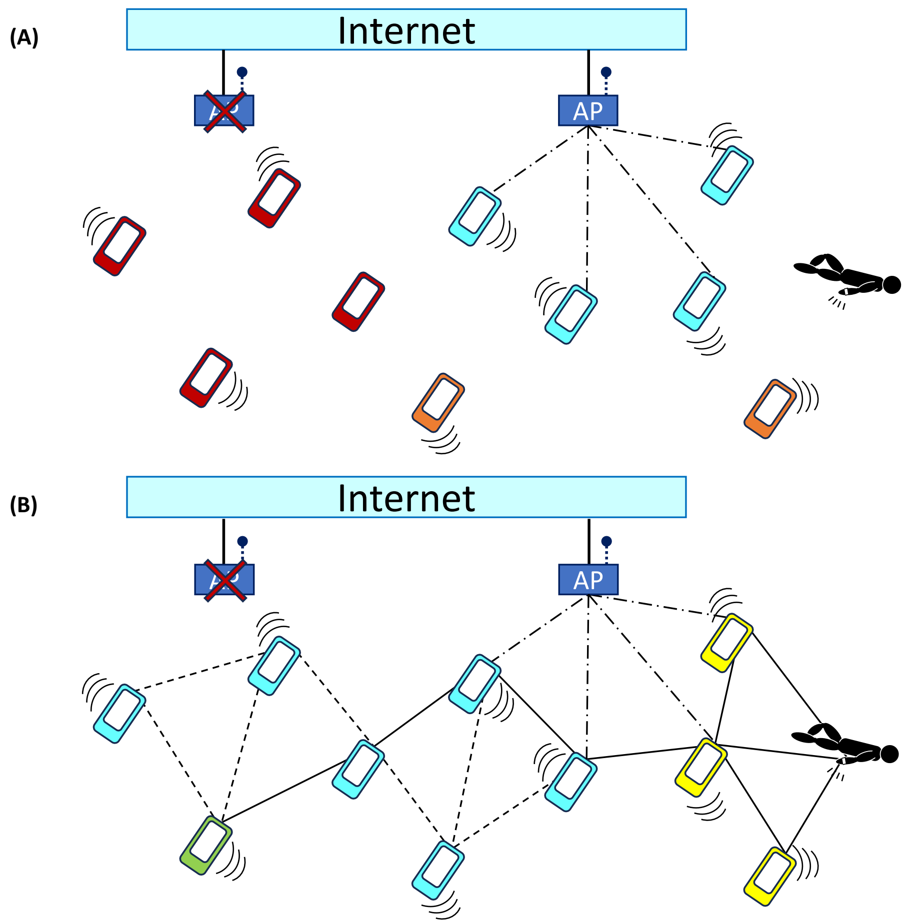

FIGURE 5 Conceptual illustrations of a conventional network (A) and an opportunistic network (B). (A) In a conventional infrastructure-based network with a star topology, only an access point (AP) and devices within its communication range (blue phones) communicate exclusively (dotted dashed lines); the AP is limited in the area to which it can refer, and devices outside its range (orange phones) lose communication. If an AP fails, all devices within its range (red phones) are unable to communicate. A sensor equipped by a out-of-hospital cardiac arrest (OHCA) patient remains unconnected and unnoticed. (B) In an opportunistic network, which has a mesh topology, each device, called a node, can communicate with each other, and even if it loses communication with the failed AP, it can still connect to other devices, providing extensive coverage. In the proposed life-saving mobile network, a sensor equipped by an OHCA patient, acting as a seed node, is connected to nearby nodes (yellow phones) and localized. Information about an emergency with its location is opportunistically transmitted in a peer-to-peer manner to the node owned by the volunteer first responder (green phone). Solid and dashed lines indicate opportunistic paths and wireless links, respectively. For details, see texts.

(individual sensors) within the network. Although GPS is a powerful localization tool, it is too costly to equip all nodes with GPS. Therefore, the benefits of providing GPS functionality to anchor nodes have been reported.[70,71] The traditional localization technique consists of physical measurements of radio signals, such as energy or received signal strength, direction of arrival, and time delay of arrival, and based on these, various advanced localization techniques have been announced and applied to date.[70]

8 | LIFE-SAVING MOBILE NETWORK CONCEPT

To the best of our knowledge, the specific methodology of using OppNet or WSN technology to locate an OHCA event has not yet been proposed in the literature. These network technologies can be used to create a network that includes potential victims, rescuers, and defibrillators. This life-saving mobile network (LMN) is simple and all the necessary fundamental technologies are being eagerly researched and will be put into practice in the near future. The following is a tentative proposal of what can be done at this time, and we would like readers of this article to develop it further.

The starting point for building the LMN is a device equipped with multisensors, such as a commercially available smartwatch. When a person experiencing sudden OHCA wears a device which can correctly detect a serious abnormality in their condition, the device can automatically transmit the radio signal as a seed node to notify nearby nodes (mostly smartphones) with direct peer-to-peer communication of the person's emergency. These nodes then cooperatively pinpoint the location of the OHCA as anchor nodes by operating their GPS as a reference and measuring distances by radio signals from the victims, similar to the localization method used in WSN (Figure 5 and Figure S1).[70] Some sensor-equipped smartwatches also have GPS functionality, so if an anomaly suggesting cardiac arrest occurs, the device can also automatically activate it and perform localization itself without the help of nearby anchor nodes. In addition, if a person is carrying a smartphone that is connected to a smartwatch that detects cardiac arrest, the location of the OHCA can be easily identified using the smartphone's GPS. The time from the onset of cardiac arrest to localization (in the absence of GPS data from the source) and its accuracy would be affected by several variables, such as the number of nearby devices, the flow of people moving around, and the length of the electrical signal range. In the LMN, there is no need to achieve precise localization to a scale of less than 1 m. Instead, the aim is to guide people in the vicinity to the location of a person who has fallen, which can be indicated by the flickering of the sensor device and a loud alarm.

After receiving the information from the OHCA victim's sensor, the nearby devices alert their owners by vibration and alarm and display a map on the screen showing the victim's location and several nearest AEDs (Figure S1). Ideally, the person receiving the alert would rush to the scene immediately, but some may not be aware of the alert or may be unable or unwilling to do so. To confirm this, the application asks the owner if they are willing to go to the site, and until a certain number of people agree, the LMN can continue to connect to other neighboring nodes and spread the information using OppNet's peer-to-peer connection. Since this confirmation requires a broadband connection and a central server, this mechanism must be a joint effort of an ad-hoc and a fixed network. If no rescuer is found, the server will also find VFRs in the same way as current VFR alerting applications do, and send an alert to them. Considering the possibility that the initial alert from the seed node's sensor could be a false one (which is not assumed to be low), it would be efficient for the EMS call center to be contacted by the VFR who received the alert and rushed to the scene.

Incorporating AEDs into the LMN is not that complicated, as accurate AED location data is already available by AED registries or various VFR alerting applications. In addition, some new generation AEDs have wireless communication capabilities to automatically transmit their self-check status to the maintenance department. As more AEDs are networked in the future, the LMN could provide more accurate AED location and availability status. The most positive changes expected from this LMN system are as follows: (1) no outdoor sudden OHCA will be missed and left untreated and (2) more CPR with an AED will be performed before EMS arrives by someone close to the incident. LMN functionalities can be integrated into existing VFR alerting applications, which allows more OHCA to be identified and nearby VFRs to be alerted earlier.

9 | SENSOR FUNCTIONALITY FOR CARDIAC ARREST DETECTION

The accuracy of cardiac arrest detection is very important and affects the availability of the LMN. That is, which sensor capabilities can quickly and accurately detect the onset of a fatal arrhythmia. Modern multi-sensor wearable devices are widely used by athletes and can measure not only their movement but also their heart rate, respiratory rate, blood oxygen saturation, ECG, and skin temperature.[72] Currently, the most likely candidates for LMN seed nodes are wristwatch-type devices, such as the Apple Watch (Apple Inc., Cupertino, California), which are used by many joggers and runners to display their speed, location, distance, and heart rate. Some also have a fall detection sensor that can automatically send an emergency call to an official EMS dispatch center.

To be used as a cardiac arrest detector, the sensitivity and combination of these sensors should be set appropriately. It must be able to distinguish between a real cardiac arrest and a confusing movement, such as a wristwatch device slipping off a person's wrist. A cardiac arrest should fulfill the following criteria: (1) a sudden and continuous cessation of a person's movement and heartbeats, (2) a fall and subsequent standstill of the device, even with continuous wrist detection and adequate body temperature, and (3) no response to a loud alarm and vibration from the device. All this is readily available in today's smartwatches. An ECG, not recorded in a stable environment, is not essential to determine the presence or absence of cardiac arrest. When we actually start CPR, we decide based only on lack of consciousness and abnormal breathing.[3,14] By developing more sophisticated software that combines sensor functions, collapse due to cardiac arrest can be correctly detected.

10 | COMMUNICATION MODALITIES CONNECTING THE LMN

In the LMN, we believe that Wi-Fi should be used for peer-to-peer communication because most current personal devices have these communication modalities and it has a relatively long communication range of about 100 m. Bluetooth is also a widely used communication method with low energy consumption, but it has a much shorter range of about 10 m.[73] Using a short-range method not only reduces the chance of a node detecting the message from the source but also requires more nodes to be located to relay the information to the destination. As Wi-Fi consumes large amounts of battery power, further development of improved Wi-Fi standards, novel economical peer-to-peer communication modalities, sophisticated control software, and efficient batteries are expected.

Unlike cellular communication, which has a communication range of several 100 m to several kilometers, a Wi-Fi-based OppNet requires each node to be within 100 m of other nodes, and there is a possibility that it will not work effectively in areas of low population density. To increase the chances of detecting sudden OHCA and extend the communication range of the LMN, it is desirable to include fixed Wi-Fi access points and smartphones that do not have the LMN application installed as nodes. With these devices in the vicinity of the OHCA's location, a system can automatically localize the scene and transmit information to the registered VFRs without the owners of the devices noticing.

11 | CHALLENGES IN BUILDING THE LMN

The foundations for building the LMN are steadily progressing, and in particular, the hardware hurdles are not significant. For example, the iPhone (Apple Inc.) with operating system version 7.0 or higher already has a communication function capable of multi-peer ad hoc Wi-Fi or Bluetooth networking.[74] The proposed network, however, certainly has problems to overcome.

First, to be included in the LMN, people have to wear the sensor device. Today, however, not only professional but also many amateur athletes, especially joggers and runners, wear a small device to track their position and performance, and smartwatches are also worn by many people in everyday life. In addition, smart rings that measure heart rate, body movement, body temperature, etc. are commercially available and their sensor accuracy is increasing.[75] Sensor devices will become lighter, more stylish, and easier to use, and more people, including older adults, will be less reluctant to wear them throughout the day. As a first step, it may be an idea to start the social implementation of the LMN through long-distance sporting events such as marathons and triathlons. On the other hand, this network would be very promising for patients who are not currently indicated for an implantable defibrillator but who are at risk, such as postmyocardial infarction patients with heart failure symptoms and a left ventricular ejection fraction slightly above 35%, or gene mutation-positive asymptomatic adolescents with relatives who died suddenly from the inherited arrhythmia syndrome.[76,77]

Second, to establish the LMN, people who volunteer as first responders will need to install specific applications to receive emergency signals. There would be a problem with the low participation rate, and due to the limitation of Wi-Fi to a range of only 100 m, more participants would be needed than with the existing VFR alerting application. To overcome this issue, the importance of the LMN intervention in saving OHCA should be continuously promoted with actual successful resuscitation cases. It is also desirable to develop a Wi-Fi or other wireless communication standard with a longer communication distance that can be installed on smartphones.

Finally, because the LMN relies on the accuracy and speed of GPS-based localization of the anchor nodes, which detect the emergency radio signal from the sensor node worn by the sudden OHCA victim, it is currently intended for outdoor use only. Due to the need for direct line-of-sight to the satellites, GPS cannot be used indoors, where two-thirds or more of OHCAs occur, indiscriminately in the United States,[78] Europe,[48,49,54,61] and Asia.[7,8,79] This, however, does not mean that the system will never be used indoors, as research into indoor localization using Wi-Fi is progressing rapidly and the results are promising.[80,81]

12 | CONCLUSIONS

Out-of-hospital cardiac arrest has been a major public health problem worldwide with a significant number of unexpected deaths each year. Patient survival rates, however, remain low at around 10% or less due to underuse of BLS and AEDs. To break this deadlock, network technology can be used. Specifically, smartphone applications activated by EMS dispatchers have been developed to alert GPS-located VFRs of a nearby OHCA. These initiatives have proven effective, with meta-analyses showing significant improvements in survival rates, leading to several guidelines recommending the use of such applications. Although there are challenges, such as the low response or acceptance rate of VFRs to attend the scene of an OHCA and false activations for EMS calls that are not appropriate for an alert, further dissemination and improvement in survival rates are expected following the results of ongoing randomized trials.

This article also described the concept of the LMN using OppNet and WSN technology. The LMN aims to improve the survival rate of sudden OHCA patients by communicating an emergency as soon as it occurs. It provides the location of the victim and the nearest AEDs to nearby smartphones or tablets using ad hoc peer-to-peer networking capabilities. This method increases the likelihood that someone will arrive on the scene and provide CPR and defibrillation faster than EMS. Although many challenges remain, they can be overcome through the combined efforts of medicine and engineering.

ACKNOWLEDGMENTS

We would like to express our gratitude to the following specialists at the University of Tokyo for their significant contributions: Associate Professor Yoshiaki Narusue and Professor Jun Yanagimoto for their outstanding expertise in engineering, Dr. John Patrick Pazdziora for splendid ALESA lecture, and Mr. Taku Arai for his insightful inputs. We would also like to deeply acknowledge the substantial contributions of the following specialists for providing the data for Table 1: Professor Taku Iwami and Dr. Takeyuki Kiguchi of Kyoto University, who oversee AED GO, Ms. Shannon Smith of the PulsePoint Foundation and Mr. David Fredman of Heartrunner Sweden AB, who also provided material for Figure 3.

FUNDING INFORMATION

N/A.

CONFLICT OF INTEREST STATEMENT

Authors declare no conflict of interests for this article.

DATA AVAILABILITY STATEMENT

Data that support the findings of this study are available upon request from the authors.

STATEMENTS RELATING TO OUR ETHICS AND INTEGRITY POLICIES

Institutional review board approval was not required as this is a review article.

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ORCID

Yu-ki Iwasaki https://orcid.org/0000-0001-8783-1365

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Hayashi M, Iwasaki Y-k. Addressing out-of-hospital cardiac arrest with current technology advances: Breaking the deadlock with a mobile network. J Arrhythmia. 2024;40:753–766. https://doi.org/10.1002/joa3.13103