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How should volunteers be dispatched to out-of-hospital cardiac arrest cases?

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1 Introduction

A person experiencing an out-of-hospital cardiac arrest (OHCA) requires urgent medical attention. Survival rates are low, but increase with rapid initiation of cardiopulmonary resuscitation, defibrillation and other more advanced treatments. Accordingly, OHCA calls are among the most urgent faced by emergency medical services (EMS).

Smartphone-enabled schemes like GoodSAM [1] and PulsePoint [3] can help.When an OHCA call is received, volunteers close to the OHCA can be alerted through an app on their phone. Volunteers need not respond, but when they do they proceed to the scene of the OHCA and render assistance. An ambulance also responds, so the workload of ambulances is unaffected. If a volunteer arrives at the scene first, then they render assistance until an ambulance crew arrives. Ambulance response times can vary but are often on the order of 9 minutes. Thus, with sufficient volunteer density, volunteers are likely to arrive before the ambulance, thereby improving survival rates.

There is a growing medical literature on volunteer schemes for OHCA that primarily focuses on data analysis. [4] gives an overview and develops stochastic models that can help determine the number and location of volunteers needed to materially improve survival rates. Here we discuss a problem related to volunteer *dispatch*.

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When an OHCA call is received, software locates the volunteers that are within (say) 400 meters of the call. The number and location of such volunteers can then be viewed as known (deterministic). The ambulance being dispatched is also known. We want to choose which volunteers to alert and when to alert them, so as to maximize the probability of survival or some other measure of quality of life. Volunteers may respond or not, and some proceed to the call. Survival rates are decreasing in the response time, so it is mathematically optimal to immediately alert *all* nearby volunteers. This policy is impractical; it could lead to volunteers receiving many alerts or to many volunteers arriving on scene, both of which are believed to reduce acceptance probabilities in the future. Similar fatigue issues arise in volunteer schemes more generally [2].

Thus, the problem is to choose which volunteers should receive alerts and when, to maximize survival rates, while keeping the total number of alerts to a minimum. We provide a statement of this problem and discuss solution approaches and extensions.

There is no true queueing in this problem, since OHCA calls are so infrequent and volunteers are so numerous (in active systems) that the chance of overlapping volunteer needs is negligible. Yet mathematical techniques commonly used in queueing analysis seem appropriate. Moreover, volunteers play the role of spatially distributed, randomly available servers. If the scope of these systems was to increase sufficiently to encompass EMS calls beyond OHCA, as is envisaged by some organizations, then volunteers could become busy enough that queueing effects would arise. Such an innovation could lead to a fundamental reimagining of EMS operations.

2 Problem statement

Suppose an OHCA is confirmed at the emergency call center at time $t = 0$. An ambulance is subsequently dispatched to the call and has a (random) response time T_0. Let $n \geq 0$ be the number of volunteers who are close enough to the call to potentially materially affect the survival probability. Let T_i be the travel time of Volunteer i after they are alerted, $i = 1, 2, \ldots, n$ the distribution of which may depend on the location of the call, e.g., downtown Manhattan or a rural setting. Let $A_i = 1$ if the ith volunteer will accept an alert, and equal 0 otherwise. For simplicity, we ignore the possibility that an alerted volunteer does not accept but responds anyway, or that a volunteer accepts the alert but does not respond. Define $A_0 = 1$ (the ambulance always responds).

Let D_i be the dispatch (alert) time of the ith volunteer, with $D_i = \infty$ if the ith volunteer is not dispatched, $i = 1, 2, \ldots, n$. These are decision variables that may also be chosen over time, depending on knowledge of the system. Let D_0 be the ambulance dispatch time.

Let $N = \sum_{i=1}^{n} 1(D_i < \infty)$ be the number of alerted volunteers, and let

$$R = \min\{D_i + T_i : i = 0, 1, \ldots, n | A_i = 1\}$$

be the response time to the OHCA. Let $f : [0, \infty] \to [0, 1]$ be the probability of survival as a function of response time, which we assume is decreasing. For simplicity we do not distinguish between ambulance and volunteer response here, though that is important in practice. Estimates of f and more complex versions exist; see [4].

The problem we wish to solve is to maximize the probability of survival subject to a bound on the expected number of alerted volunteers, i.e., to maximize $Ef(R)$ subject to $E(N) \leq b$, where b is a budget on the number of volunteer alerts. The decisions are the dispatch times $D_1, D_2, \ldots, D_n$. Here N is potentially random if the dispatch times are chosen adaptively over time. Instead of bounding the expected value, one could use a probabilistic constraint of the form $P(N > a) \leq \alpha$ for constants a and α, though we expect the formulation we have given to be more tractable.

For calls where all volunteers are far away, survival is unlikely even if those volunteers are dispatched. Then, overall survival rates across many OHCA calls could be increased by trading off dispatch decisions *between* calls while ensuring overall that $E(N) \leq b$. We do not pursue such tradeoffs here, though they are worthy of study.

3 Discussion

In some real systems, all dispatch decisions are made at time 0. Then, if $D_i < \infty$, $D_i = 0$ is optimal and standard. Is it worthwhile to instead make these decisions adaptively?

If dispatch decisions are made adaptively, then the natural formulation is through a dynamic program with a state space that reflects the alerts sent, volunteer responses received and the departure times of accepting volunteers. This state space could be large, making it challenging to find even a near-optimal policy.

Assuming that the probability a volunteer accepts an alert is a decreasing function of their distance to the OHCA and response times are increasing deterministic functions of distance to the call, then an exchange argument shows that it is optimal to dispatch volunteers in increasing order of distance to the OHCA. A dynamic program must still be solved, but the state space of the dynamic program is reduced, since one can replace the departure times of accepting volunteers with the time at which the first volunteer will arrive. Even this reduced state space could still be large.

An extension where some volunteers are dispatched directly to the OHCA, while others are routed to pick up a nearby automated external defibrillator (AED), would be valuable. (Related work on AED positioning in a city that does not account for volunteer dispatching is referenced in [4].) Finally, these dynamic programs could be solved in real time, perhaps necessitating trade-offs between speed and model fidelity/quality of solution, or solved offline to obtain policies that can be rapidly employed in real time.

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