ORIGINAL RESEARCH

Clinical Predictive Models of Sudden Cardiac Arrest: A Survey of the Current Science and Analysis of Model Performances

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BACKGROUND: More than 500,000 sudden cardiac arrests (SCAs) occur annually in the United States. Clinical predictive models (CPMs) may be helpful tools to differentiate between patients who are likely to survive or have good neurologic recovery and those who are not. However, which CPMs are most reliable for discriminating between outcomes in SCA is not known.

METHODS AND RESULTS: We performed a systematic review of the literature using the Tufts PACE (Predictive Analytics and Comparative Effectiveness) CPM Registry through February 1, 2020, and identified 81 unique CPMs of SCA and 62 subsequent external validation studies. Initial cardiac rhythm, age, and duration of cardiopulmonary resuscitation were the 3 most commonly used predictive variables. Only 33 of the 81 novel SCA CPMs (41%) were validated at least once. Of 81 novel SCA CPMs, 56 (69%) and 61 of 62 validation studies (98%) reported discrimination, with median c-statistics of 0.84 and 0.81, respectively. Calibration was reported in only 29 of 62 validation studies (46.8%). For those novel models that both reported discrimination and were validated (26 models), the median percentage change in discrimination was −1.6%. We identified 3 CPMs that had undergone at least 3 external validation studies: the out-of-hospital cardiac arrest score (9 validations; median c-statistic, 0.79), the cardiac arrest hospital prognosis score (6 validations; median c-statistic, 0.83), and the good outcome following attempted resuscitation score (6 validations; median c-statistic, 0.76).

CONCLUSIONS: Although only a small number of SCA CPMs have been rigorously validated, the ones that have been demonstrate good discrimination.

Key Words: cardiac arrest ■ prediction ■ sudden cardiac death

Sudden cardiac arrest (SCA) is the abrupt cessation of cardiac activity such that an individual becomes unresponsive, without breathing or signs of circulation.¹ In the United States, there are ≈360,000 out-of-hospital cardiac arrest (OHCA) events and 210,000 in-hospital cardiac arrest (IHCA) events annually.² Prognosis after an SCA is dismal, with survival from OHCA and IHCA estimated to be 10%³ and 25%,⁴ respectively; rates of good neurologic outcome are even lower. Because of the often-precipitous nature of SCA, surrogate decision makers may find themselves in the position of having to make unexpected, difficult choices about care for these patients. Critical decisions, such as withdrawal of care, tracheostomy or percutaneous gastrostomy tube placement, and subsequent changes in code status, are particularly difficult when overall prognosis is unclear. Effectively differentiating patients who are likely to do well after an SCA event from those who are unlikely to do well may help to guide these decisions. Unfortunately, this task...
CLINICAL PERSPECTIVE

What Is New?
- Sudden cardiac arrest (SCA) is a common but disastrous event that can leave both physicians and surrogate decision makers in the difficult position of determining treatment plans in the setting of unclear prognosis; clinical predictive models represent objective, quantitative tools for guiding this type of decision on the behalf of critically ill victims of SCA.
- There are many unique clinical predictive models available for use in SCA, and these tools generally have excellent ability to discriminate between those patients who are likely and those who are unlikely to survive with good neurologic outcome following SCA; only a few of these models have been rigorously validated.

What Are the Clinical Implications?
- The out-of-hospital cardiac arrest score, the cardiac arrest hospital prognosis score, and the good outcome following attempted resuscitation score are the 3 most rigorously validated tools for predicting the prognosis of SCA victims; however, the predictions made using these tools should be interpreted cautiously and in the context of an individual patient’s clinical picture to avoid inappropriate early withdrawal of life-sustaining treatment.

Methods

The data that support the findings of this study are available from the corresponding author on reasonable request.

Model and Validation Identification

We performed a systematic review of novel SCA CPMs and their validations (Figure 1). We included previously identified SCA CPMs from the Tufts PACE (Predictive Analytics and Comparative Effectiveness) CPM Registry. The registry, which is free and available to the public at http://pace.tuftsmedicalcenter.org/com, contains a field synopsis of CPMs in cardiovascular disease, including SCA, published between January 1990 and December 2015. These methods have been previously reported.5 We identified additional English-language abstracts containing potential SCA CPMs via a targeted PubMed search (Figure S1) of the OVID Medline database extending through February 1, 2020. Two independent reviewers screened potential abstracts using Abstrackr, a semiautomated online screening program. Discrepancies were discussed until consensus was achieved. We then selected abstracts for full-text review if they met the following inclusion criteria: (1) made specific mention of multivariate modeling, (2) specified SCA as the index condition, and (3) were based on data from a primarily adult population. We then doubly screened full-text publications and included them for further analysis if, in addition to meeting the inclusion criteria, they contained a novel, useable (meaning that an end user could generate an outcome prediction given knowledge of the appropriate set of patient variables) SCA CPM. We identified CPM validation studies by performing a Scopus citation search on all novel SCA CPMs identified as above. Two independent reviewers screened abstracts and full-text publications in the same manner as for novel models. We included validation studies for further analysis if they assessed a previously published SCA CPM in a population temporally and/or spatially distinct from the population used in the initial development of that model. Novel models that were incidentally identified during validation search were also included, and the cycle of validation search was repeated until no further novel models were identified.

Data Extraction and Statistical Analysis

We extracted data on the studied population, the proposed model, and SCA outcomes from both novel model and validation studies in accordance
with the checklist for systematic reviews of prediction modeling studies. Collected fields included location of data origin, whether data were collected prospectively or retrospectively, the approach to and amount of missingness in the data set, time frame of the predicted outcome, sample size, number of SCA events and whether the arrest occurred out of hospital or in hospital, model discrimination, and calibration. A modified version of the Prediction Model Risk of Bias Assessment Tool was used to assess the risk of bias in model development and applicability of the models by a trained research assistant. The simplified version, Prediction Model Risk of Bias Assessment Tool Short Form, is a structured judgment system focusing on the analytic items in Prediction Model Risk of Bias Assessment Tool. It was collaboratively developed by clinicians and modeling experts for use and tested for agreement with the complete Prediction Model Risk of Bias Assessment Tool on models included in the Tufts PACE Center CPM Registry; the results are currently pending publication. We categorized the time frame of predicted outcome into 3 categories: (1) early, through 1 day after SCA, (2) intermediate, >1 day post-SCA to hospital discharge, and (3) long-term, beyond hospital discharge. We used the c-statistic (or area under the curve of the receiver operator curve) to assess model discrimination. Because the c-statistic is bounded between 0.5 and 1.0, we used percentage change in discrimination (equation 1) to make direct comparisons between discrimination of novel models and validation studies.

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\text{Percent change in discrimination} = \left( \frac{\text{c-statistic}_{\text{Validation}} - \text{c-statistic}_{\text{Novel}}}{\text{c-statistic}_{\text{Novel}} - 0.5} \right) \times 100.
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RESULTS

Novel SCA CPMs

We identified 81 unique CPMs of SCA published between July 1981 and February 2020 (Figure 2). Table 1 summarizes characteristics of the populations used in these novel SCA CPMs, and Table 2 presents detailed information on the complete set of identified models. Herein, models are identified using PubMed identification numbers; a model identification number further differentiates between multiple publications.

![Figure 2](image_url)  
**Figure 2.** Histogram showing the number of both novel sudden cardiac arrest clinical predictive models (blue) and validation (orange) studies that were published per 5-year interval between January 1980 and February 2020.

### Table 1. Characteristics of the SCA CPM Derivation and Validation Populations

| Characteristic | Novel Model | Validation Study |
|----------------|-------------|------------------|
| No. of models  | 81          | 62               |
| Average age, y | 65 (61–67)  | 65 (62–70)       |
| Men, %         | 66 (60–75)  | 63 (59–70)       |
| Sample size    | 591 (140–1028) | 430 (212–1657) |

Data are given as median (interquartile range), unless otherwise indicated. CPM indicates clinical predictive model, and SCA, sudden cardiac arrest.
Table 2. List of the Identified SCA CPMs With Information Detailing the Derivation Population, Including Whether These Models Were Derived for a More Specific Index Condition (eg, in Patients Undergoing ECPR or TTM), Associated Model Outcomes, Discrimination if Investigated, and Number of External Validation Studies

| PMID       | Model No. | Population Size | OHCA vs IHCA | Specific Index Condition | Outcome Type | Outcome Time Frame | % Good Outcome | C-Statistic | No. of External Validations |
|------------|-----------|-----------------|--------------|--------------------------|--------------|--------------------|----------------|------------|------------------------------|
| 13150729   | 1         | 112             | Mixed        | None                     | Survival     | Intermediate       | 55             | 0.83       | 0                            |
| 15780405   | 1         | 6179            | Mixed        | None                     | Survival     | Intermediate       | 11             | NR         | 0                            |
| 16610181   | 1         | 710             | IHCA         | None                     | Survival     | Intermediate       | 28             | 0.78       | 0                            |
| 16610181   | 2         | 198             | IHCA         | None                     | Survival     | Intermediate       | 47             | 0.8        | 0                            |
| 22464192   | 1         | 347             | OHCA         | None                     | Neurologic   | Intermediate       | 11             | NR         | 0                            |
| 25510111   | 1         | 2235            | Mixed        | None                     | Survival     | Intermediate       | 16             | NR         | 1                            |
| 27419774   | 1         | 140             | IHCA         | None                     | Survival     | Intermediate       | 24             | NR         | 2                            |
| 72417285   | 1         | 611             | OHCA         | None                     | Survival     | Intermediate       | 19             | NR         | 2                            |
| 93964219   | 1         | 1872            | OHCA         | None                     | Survival     | Intermediate       | 31             | 0.65       | 0                            |
| 94625997   | 1         | 127             | OHCA         | Witnessed arrest; cardiac cause | Survival | Intermediate | 42             | 0.81       | 1                            |
| 94625997   | 2         | 127             | OHCA         | Witnessed arrest; cardiac cause | Neurologic | Intermediate | 39             | 0.89       | 1                            |
| 95478422   | 1         | 100             | OHCA         | Cardiac cause; ventricular fibrillation | Survival | Intermediate | 29             | NR         | 0                            |
| 12533389   | 1         | 741             | IHCA         | None                     | Survival     | Short-term         | 10             | NR         | 1                            |
| 12533389   | 2         | 707             | IHCA         | None                     | Survival     | Short-term         | 9              | NR         | 0                            |
| 12626988   | 1         | 34              | Mixed        | None                     | Neurologic   | Intermediate       | 47             | NR         | 0                            |
| 15246581   | 1         | 219             | IHCA         | None                     | Survival     | Intermediate       | 15             | NR         | 0                            |
| 15246581   | 2         | 219             | IHCA         | None                     | Survival     | Long-term          | 14             | NR         | 0                            |
| 15246581   | 3         | 219             | IHCA         | None                     | Survival     | Long-term          | 11             | NR         | 0                            |
| 15531065   | 1         | 754             | OHCA         | None                     | Survival     | Intermediate       | 1              | NR         | 0                            |
| 15531065   | 2         | 754             | OHCA         | None                     | Neurologic   | Intermediate       | 2              | NR         | 0                            |
| 15531065   | 3         | 754             | OHCA         | None                     | Neurologic   | Intermediate       | 2              | NR         | 0                            |
| 17082207   | 1         | 130             | OHCA         | None                     | Neurologic   | Intermediate       | 22             | 0.82       | 9                            |
| 18573589   | 1         | 1028            | OHCA         | Cardiac cause; shockable rhythm | Survival | Long-term          | 20             | 0.74       | 0                            |
| 18584503   | 1         | 748             | OHCA         | Ventricular fibrillation | Survival     | Short-term         | NR             | NR         | 0                            |
| 20655699   | 1         | 591             | OHCA         | None                     | Survival     | Short-term         | 21             | 0.83       | 0                            |
| 20655699   | 2         | 591             | OHCA         | None                     | Survival     | Intermediate       | 13             | 0.88       | 0                            |
| 20655699   | 3         | 591             | OHCA         | None                     | Survival     | Long-term          | 10             | 0.91       | 0                            |
| 21482007   | 1         | 285             | OHCA         | Shockable rhythm       | Neurologic   | Long-term          | 32             | 0.85       | 1                            |
| 21482007   | 2         | 577             | OHCA         | Nonshockable rhythm    | Neurologic   | Long-term          | 6              | 0.89       | 1                            |
| 21515626   | 1         | 5471            | OHCA         | None                     | Survival     | Intermediate       | 43             | 0.71       | 4                            |
| 21759698   | 1         | 457             | Mixed        | None                     | Survival     | Long-term          | 47             | NR         | 2                            |
| 22281226   | 1         | 66              | OHCA         | TTM                     | Neurologic   | Intermediate       | 61             | 0.95       | 0                            |
| 22641228   | 1         | 28629           | IHCA         | None                     | Neurologic   | Intermediate       | 25             | 0.8        | 2                            |
| 23844724   | 1         | 307896          | OHCA         | None                     | Survival     | Long-term          | 4              | 0.79       | 1                            |
| 23844724   | 2         | 307896          | OHCA         | None                     | Neurologic   | Long-term          | 2              | 0.85       | 1                            |
| 24018585   | 1         | 22626           | IHCA         | None                     | Neurologic   | Long-term          | 11             | 0.78       | 6                            |
| 24107638   | 1         | 38092           | IHCA         | None                     | Neurologic   | Long-term          | 10             | 0.76       | 2                            |

(Continued)
| PMID         | Model No. | Population Size | OHCA vs IHCA | Specific Index Condition | Outcome Type | Outcome Time Frame | % Good Outcome | C-Statistic | No. of External Validations |
|--------------|-----------|-----------------|--------------|--------------------------|--------------|--------------------|----------------|-------------|-----------------------------|
| 24107638     | 2         | 38 092          | IHCA         | None                     | Neurologic   | Long-term          | 10             | 0.73        | 2                           |
| 24309445     | 1         | 750             | OHCA         | None                     | Survival     | Long-term          | 6              | NR          | 0                           |
| 24830872     | 1         | 14 688          | IHCA         | None                     | Survival     | Short-term          | 45             | 0.73        | 2                           |
| 24830872     | 2         | 14 688          | IHCA         | None                     | Survival     | Intermediate       | 20             | 0.81        | 2                           |
| 24960427     | 1         | 1068            | OHCA         | None                     | Survival     | Long-term          | 40             | NR          | 1                           |
| 25443259     | 1         | 192             | IHCA         | None                     | Survival     | Intermediate       | 32             | 0.86        | 1                           |
| 25828128     | 1         | 32              | Mixed        | TTM; ventricular fibrillation | Neurologic   | Long-term          | 47             | 0.98        | 1                           |
| 25911585     | 1         | 92              | OHCA         | TTM                      | Survival     | Long-term          | 54             | 0.82        | 0                           |
| 25911585     | 2         | 66              | OHCA         | TTM                      | Survival     | Long-term          | 67             | 0.88        | 0                           |
| 26322336     | 1         | 96              | OHCA         | None                     | Neurologic   | Intermediate       | 20             | 0.84        | 0                           |
| 26897616     | 1         | 819             | OHCA         | None                     | Neurologic   | Intermediate       | 27             | 0.93        | 6                           |
| 26889743     | 1         | 207             | OHCA         | Cardiac cause            | Survival     | Intermediate       | 65             | 0.81        | 1                           |
| 28410589     | 1         | 933             | OHCA         | Cardiac cause; TTM       | Neurologic   | Long-term          | 47             | 0.84        | 0                           |
| 28490379     | 1         | 151             | OHCA         | TTM                      | Neurologic   | Intermediate       | 42             | 0.96        | 0                           |
| 28528323     | 1         | 122             | OHCA         | TTM                      | Neurologic   | Intermediate       | 27             | 0.82        | 1                           |
| 28629472     | 1         | 687             | OHCA         | Cardiac cause; TTM       | Neurologic   | Long-term          | 51             | 0.84        | 0                           |
| 28647407     | 1         | 547             | OHCA         | None                     | Survival     | Short-term          | 59             | 0.86        | 0                           |
| 28859880     | 1         | 111             | Mixed        | ECPR                     | Survival     | Intermediate       | 19             | 0.88        | 0                           |
| 29074504     | 1         | 638             | OHCA         | None                     | Survival     | Intermediate       | 81             | 0.73        | 0                           |
| 29317350     | 1         | 420 959         | OHCA         | None                     | Neurologic   | Intermediate       | 1              | NR          | 0                           |
| 29481910     | 1         | 286             | OHCA         | Hypothermic arrest; ECPR | Survival     | Intermediate       | 37             | 0.9         | 1                           |
| 29580950     | 1         | 658             | OHCA         | Hypothermic arrest; ECPR | Neurologic   | Continuous         | 40             | NR          | 0                           |
| 29677083     | 1         | 81              | OHCA         | Hanging-induced arrest; TTM | Survival     | Intermediate       | 25             | 0.91        | 0                           |
| 29677083     | 2         | 81              | OHCA         | Hanging-induced arrest; TTM | Neurologic   | Intermediate       | 20             | 0.86        | 0                           |
| 29942359     | 1         | 129             | OHCA         | None                     | Neurologic   | Intermediate       | 30             | 0.84        | 1                           |
| 30001950     | 1         | 51              | OHCA         | TTM                      | Neurologic   | Long-term          | 43             | 0.9         | 1                           |
| 30261969     | 1         | 198             | OHCA         | Patients undergoing angiography | Survival     | Long-term          | 53             | NR          | 1                           |
| 30292802     | 1         | 456             | OHCA         | None                     | Neurologic   | Long-term          | 19             | 0.82        | 0                           |
| 30345531     | 1         | 788             | Mixed        | None                     | Survival     | Continuous         | 52             | NR          | 0                           |
| 30413210     | 1         | 107             | OHCA         | Cardiac cause; TTM       | Neurologic   | Long-term          | 47             | 0.92        | 0                           |
| 30601168     | 1         | 19 809          | OHCA         | None                     | Survival     | Short-term          | 41             | NR          | 0                           |
| 30650128     | 1         | 40              | OHCA         | None                     | Survival     | Long-term          | 30%            | 0.94        | 0                           |
| 30650128     | 2         | 40              | OHCA         | None                     | Survival     | Long-term          | 30             | 0.95        | 0                           |
| 30650128     | 3         | 40              | OHCA         | None                     | Survival     | Long-term          | 30             | 0.99        | 0                           |
| 30807816     | 1         | 580             | Mixed        | None                     | Neurologic   | Intermediate       | 37             | 0.88        | 0                           |
| 30819521     | 1         | 852             | OHCA         | None                     | Neurologic   | Intermediate       | 4              | 0.82        | 1                           |
| 30848327     | 1         | 3855            | OHCA         | None                     | Neurologic   | Intermediate       | 34             | NR          | 0                           |
| 31153943     | 1         | 460             | OHCA         | TTM                      | Neurologic   | Long-term          | 38             | 0.89        | 1                           |
| 31153943     | 2         | 460             | OHCA         | TTM                      | Neurologic   | Long-term          | 29             | 0.9         | 0                           |

(Continued)
models contained within a single publication. Fifty-five of those models (68%) predicted outcomes following OHCA, 17 (21%) following IHCA, and 9 (11%) following a mixture of both. Nine (11%) models predicted early outcomes, 42 (52%) predicted intermediate time frame outcomes, and 28 (35%) predicted long-term outcomes. Thirty-one (38%) models used European populations during derivation, 24 (30%) used North American populations, and 17 (21%) used Asian populations. Thirty-one (38%) models were developed with prospective cohort data, and 49 (61%) models were developed using retrospective cohort data. Thirty-three (41%) models reported their approach to missingness, and 27 (33%) models reported amount of missingness in the derivation cohort. Models took various forms, with point score-based models constituting 35 (43%) models, logistic regression constituting 29 (36%) models, and characteristic decision trees constituting 16 (20%) models. The median sample size of derivation populations was 591 (interquartile range [IQR], 140–1028). The number of studies at low risk of bias was 6 (7%); the remaining 75 (93%) were high risk of bias. The median number of predictive covariates was 5 (IQR, 3–6), and the 3 most commonly used covariates were initial rhythm (n=51, 63%), age (n=42, 52%), and the duration of cardiopulmonary resuscitation (n=31, 38%) (Figure 3). Of models that reported discrimination (n=56, 69%), the median c-statistic was 0.84 (IQR, 0.80–0.89) (Figure 4A).

Validation Studies

We identified 62 SCA CPM validation studies published between April 1997 and February 2020 (Figure 1). Table 1 summarizes characteristics of the populations used in these validation studies, and Table 3 presents detailed information on the complete set of identified validation studies. Of the 81 novel SCA CPMs, 33 (41%) were validated at least once, and only 4 (5%) were validated at least 3 times (Figure 5). The 3 most rigorously validated models were the OHCA score,23 the cardiac arrest hospital prognosis score,42 and the good outcome following attempted resuscitation score33 (Table 4). All but one validation study reported discrimination (n=61, 98%). The median c-statistic was 0.81 (IQR, 0.74–0.85) (Figure 4B). Only 29 of the 62 validations (47%) reported information on calibration. Of the 33 validated models,

![Figure 3](image-url)  
**Figure 3.** The top 10 most frequently included predictive covariates (or covariate classes) included in novel sudden cardiac arrest clinical predictive models.  
CPR indicates cardiopulmonary resuscitation.
discrimination was reported in both model generation and validation publications for 26 models. For these models, the median percentage change in discrimination was −1.6% (IQR, −10.6% to 8.2%) (Figure 6).

IHCAs Versus OHCAs

We stratified SCA CPMs by whether the index SCA occurred in out-of-hospital or in-hospital settings. We identified 55 models (68%) of OHCA with a median derivation population of 577 (IQR, 128–835) and median rate of events per variable of 17 (IQR, 8–56). We identified 17 models (21%) of IHCA with median derivation population of 710 (IQR, 219–22,626) and median rate of events per variable of 35 (IQR, 9–515). Discrimination was higher for OHCA models (median c-statistic, 0.85; IQR, 0.82–0.90) than for IHCA models (median c-statistic, 0.78; IQR, 0.75–0.80).

DISCUSSION

In the present study, we have shown that there are a broad variety of models available for predicting clinical outcomes following SCA. We found that the median c-statistic of novel SCA CPMs was 0.84, suggesting that in general these models are good at discriminating between patients who are likely to have a good outcome from those who are likely to have a poor outcome after a SCA (to put this in context, the cardiac failure or dysfunction, hypertension, age ≥75 [doubled], diabetes, stroke [doubled], vascular disease, age 65–74 and sex category [female] score which has been widely used for determining stroke risk in patients with atrial fibrillation had discriminations of 0.61 and 0.67 during derivation and validation, respectively95,96).

This strong discrimination was maintained during external validation; in SCA CPMs that were validated at least once, matched comparison of discrimination from model generation and validation studies showed a median percentage change in discrimination of only −1.6%. This is in stark contrast to CPMs in other areas of cardiovascular disease. For example, we have previously examined CPMs related to valvular heart disease. The percentage change in discrimination of valvular heart disease CPMs was on the order of −30%.97 In another study in which we validated 3 major CPMs of acute heart failure, we found percentage decrements in discrimination of between −19% and −30%.98 Other groups have found similar effects in carotid revascularization99 and hospital readmission following acute myocardial infarction.100

Predictive Variables in SCA CPMs

One of the unique aspects of SCA CPMs compared with CPMs in other cardiovascular diseases is that predictions are made not just on characteristics of the individual patient, but also on characteristics of the cardiac arrest that a particular patient experiences. We found that the most frequently used predictive variables were event specific (eg, duration of cardiopulmonary resuscitation and initial SCA cardiac rhythm) rather than patient specific (eg, age and sex). The fact that these variables were so frequently selected after multivariate analysis suggests that they are strong predictors of outcome. This reliance on event-specific variables may make SCA CPMs less sensitive to difference in the composition of patient population.

From a clinical perspective, this finding that predictions were largely independent of patient-specific variables is counterintuitive. Several studies have shown that comorbidities, such as diabetes mellitus,101 liver disease,102 and malignancy,103,104 are independent predictors of poor outcome in SCA. One possible explanation for this discrepancy is that there is covariance between these comorbidity variables and other variables that are more strongly associated with SCA outcome. Nonshockable rhythm, for example, is significantly more likely in patients experiencing SCA with underlying diabetes mellitus,
## Table 3. List of the Identified Validation Studies With Information Detailing the Validation Population, Associated Outcome Rates, Discrimination, and Calibration Method if Investigated

| Validation PMID | Novel Model PMID | Model No. | Population Size | Event Rate, % | C-Statistic | Calibration Method | Calibration Reported |
|-----------------|------------------|-----------|----------------|--------------|-------------|-------------------|----------------------|
| 910761272       | 2741977          | 1         | 656            | 5            | 0.52        | No                 |                      |
| 954176473       | 9462599          | 1         | 62             | 53           | 0.92        | No                 |                      |
| 954176473       | 9462599          | 2         | 62             | 47           | 0.93        | No                 |                      |
| 1278252276      | 7241728          | 1         | 575            | 4            | 0.33        | Yes                |                      |
| 1708220773      | 17082207         | 1         | 210            | 25           | 0.88        | Yes                |                      |
| 2065569982      | 2551011          | 1         | 591            | 10           | 0.82        | No                 |                      |
| 2065569982      | 7241728          | 1         | 591            | 13           | 0.79        | No                 |                      |
| 2065569982      | 12533358         | 1         | 591            | 21           | 0.73        | No                 |                      |
| 2148200772      | 21482007         | 1         | 212            | 46           | 0.87        | No                 |                      |
| 2148200772      | 21482007         | 2         | 423            | 5            | 0.87        | No                 |                      |
| 2149410676      | 17082207         | 1         | 128            | 23           | 0.85        | Yes                |                      |
| 2151562685      | 21515626         | 1         | 2218           | 44           | 0.73        | No                 |                      |
| 2228112275      | 17082207         | 1         | 122            | 35           | 0.79        | No                 |                      |
| 2384472458      | 23844724         | 1         | 82 330         | 5            | 0.81        | No                 |                      |
| 2384472458      | 23844724         | 2         | 82 330         | 2            | 0.88        | No                 |                      |
| 2410763874      | 24107638         | 1         | 14 435         | 12           | 0.73        | No                 |                      |
| 2410763874      | 24107638         | 2         | 14 435         | 12           | 0.71        | No                 |                      |
| 2483087263      | 24830872         | 1         | 7791           | 45           | 0.72        | Yes                |                      |
| 2483087263      | 24830872         | 1         | 1657           | 46           | 0.72        | Yes                |                      |
| 2483087263      | 24830872         | 2         | 7791           | 18           | 0.81        | Yes                |                      |
| 2483087263      | 24830872         | 2         | 1657           | 19           | 0.80        | Yes                |                      |
| 2496042778      | 24960427         | 1         | 297            | 58           | 0.81        | No                 |                      |
| 2563896977      | 21756969         | 1         | 393            | 41           | 0.82        | Yes                |                      |
| 2563896977      | 21756969         | 1         | 214            | 41           | 0.83        | Yes                |                      |
| 2582812886      | 25828128         | 1         | 29             | 66           | 0.89        | Yes                |                      |
| 2639384984      | 2741977          | 1         | 26 327         | 24           | 0.69        | No                 |                      |
| 2639384984      | 22641228         | 1         | 26 327         | 24           | 0.79        | Yes                |                      |
| 2649716196      | 26497161         | 1         | 367            | 33           | 0.85        | Yes                |                      |
| 2649716196      | 26497161         | 1         | 1129           | 25           | 0.91        | Yes                |                      |
| 2668974387      | 26689743         | 1         | 96             | 65           | 0.82        | No                 |                      |
| 2740289496      | 24018985         | 1         | 287            | 16           | 0.85        | No                 |                      |
| 2804938992      | 24107638         | 1         | 287            | 16           | 0.77        | No                 |                      |
| 2804938992      | 24107638         | 2         | 287            | 16           | 0.71        | No                 |                      |
| 2835613456      | 21515626         | 1         | 680            | 50           | 0.71        | Yes                |                      |
| 2841058984      | 17082207         | 1         | 933            | 47           | 0.75        | Yes                |                      |
| 2841058984      | 26497161         | 1         | 933            | 47           | 0.75        | Yes                |                      |
| 2852083363      | 28520833         | 1         | 344            | 21           | 0.81        | Yes                |                      |
| 2950015482      | 17082207         | 1         | 150            | 22           | 0.57        | No                 |                      |
| 2972320195      | 17082207         | 1         | 173            | 31           | 0.74        | No                 |                      |
| 2972320195      | 24018985         | 1         | 717            | 22           | 0.82        | Yes                |                      |
| 2994235966      | 29942359         | 1         | 31             | NR           | 0.90        | No                 |                      |
| 3000195080      | 30001950         | 1         | 91             | 46           | 0.82        | No                 |                      |
| 3013838378      | 22641228         | 1         | 796            | 12           | 0.79        | Yes                |                      |
| 3026196997      | 30261969         | 1         | 67             | NR           | NR          | No                 |                      |
| 3039103988      | 17082207         | 1         | 349            | 43           | 0.81        | Yes                |                      |

(Continued)
liver disease, and malignancy. In SCA CPMs identified in this study, we identified several examples of comorbidity (eg, diabetes mellitus, chronic kidney disease, and malignancy) dropout in favor of initial rhythm or other strong event-specific variables.

Impacts of Location of Arrest
Models that examined outcomes after OHCA performed better on average than those that examined outcomes after IHCA, with median C-statistics of 0.85 and 0.78, respectively. Although the CPMs for these 2 different populations share many of the same predictive variables, the magnitudes/values of these variables are different. Medical response times to OHCA are slower compared with IHCA, it follows that much longer durations of no-flow and low-flow circulation are found in OHCA. Large surveys of both OHCA and IHCA have also shown that initial rhythm is less likely to be shockable in OHCA (13%) compared with IHCA (21%). The impact of arrest location on variable magnitudes is further complicated by the fact that the directionality of these changes may differ depending on the variable. For example, although OHCA tends to be longer and less likely to be shockable than IHCA, victims of IHCA tend to be sicker and have higher burdens of comorbidity at baseline compared with their OHCA counterparts.

Patients experiencing OHCA also have lower rates of survival and neurologic recovery than those experiencing IHCA. Although sensitivity and specificity are often assumed to be independent of the outcome rate in a population, these metrics can differ based on the underlying case mix of the population being studied. Discrimination is thus affected by heterogeneity and will tend to be better in more heterogeneous populations.

Finally, OHCA models were derived from smaller populations than IHCA models and had lower numbers of positive outcome per model covariate. This may have predisposed these OHCA models to relative overfitting compared with their IHCA counterparts and may in part explain the better discrimination of OHCA models.

Clinical Implications
The primary clinical use of these CPMs is in assisting physicians and surrogate decision makers with

| Table 3. Continued |
|---------------------|
| Validation PMID     | Novel Model PMID | Model No. | Population Size | Event Rate, % | C-Statistic | Calibration Reported |
| 30391369**         | 26497161       | 1         | 349             | 43            | 0.86        | Yes                   |
| 30447262**         | 21515628       | 1         | 2041            | 29            | 0.76        | Yes                   |
| 30807816**         | 17082207       | 1         | 437             | NR            | 0.86        | No                    |
| 30819521**         | 30819521       | 1         | 859             | 2             | 0.88        | Yes                   |
| 30940473**         | 29481910       | 1         | 122             | 42            | 0.82        | Yes                   |
| 30981847**         | 25443259       | 1         | 274             | 29            | 0.82        | Yes                   |
| 31078496**         | 24018585       | 1         | 2845            | 11            | 0.75        | Yes                   |
| 31078496**         | 24018585       | 1         | 16 154          | 15            | 0.76        | Yes                   |
| 31153943**         | 31153943       | 1         | 151             | 42            | 0.93        | No                    |
| 31306716**         | 17082207       | 1         | 336             | 45            | 0.79        | No                    |
| 31306716**         | 26497161       | 1         | 336             | 45            | 0.81        | No                    |
| 31512185**         | 24018585       | 1         | 403             | 17            | 0.68        | No                    |
| 31730900**         | 31730900       | 1         | 1806            | 23            | 0.88        | Yes                   |
| 31980268**         | 31980268       | 1         | 747             | 26            | 0.77        | No                    |
| 31987887**         | 26497161       | 1         | 176             | 6             | 0.81        | No                    |
| 32035177**         | 21515626       | 1         | 63 059          | 8             | 0.74        | Yes                   |

NR indicates not reported; PMID, PubMed identification number.
decisions on intensification, continuation, or withdrawal of care. For this purpose, SCA CPMs offer several advantages compared with guidance based on the anecdotal experiences of an individual physician. In studies of end-of-life counseling, miscommunication between physician and surrogate decision makers has been identified as a primary driver of inappropriately optimistic expectations of prognosis. Inappropriately optimistic expectations have been shown to significantly increase duration of intensive care unit hospitalization and cost without improving patient outcomes. Quantitative assessments of prognosis, such as those offered by SCA CPMs, also leave less room for misinterpretation than qualitative assessments.

Inappropriate early withdrawal of life-sustaining treatment attributable to perceived poor prognosis is a major cause of preventable death in victims of SCA (and may in part contribute to the high c-statistics found in these CPMs by making bad outcomes easier to predict). Two cohort studies that matched SCA victims for whom care was withdrawn before 72 hours to those who received continued treatment estimated that 16% to 19% of patients who received withdrawal of care would have otherwise gone on to have good neurologic recovery. Subjective impressions of poor prognosis from physicians are thought to be a major contributor to this inappropriate withdrawal of life-sustaining treatment. In this case, SCA CPMs have the advantage of objectivity and may help to reduce the intrusion of physician-held personal biases into discussions on withdrawal of care. Nevertheless, these theoretical advantages should be examined empirically, ideally in clinical trials.

Because prophesies of mortality can be self-fulfilling, predictions in SCA should be made with care. Identifying when medical care is likely to be futile generally requires a high degree of certainty because the consequences of a false-positive prediction are so dire. Although we identified 3 SCA CPMs (the OHCA score, the cardiac arrest hospital prognosis score, and the good outcome following attempted resuscitation score) that performed well using conventional measures of discrimination, it is unclear whether they can provide the confidence necessary to support futility claims. Any CPM-based prediction should be interpreted in the broader context of an individual patient’s overall clinical picture.

Limitations
There are several limitations to this work. Although we applied a systematic approach to the identification of novel SCA CPMs and their validations, our search was limited to the Medline and Scopus databases. It is possible that there are models and/or validation studies present in alternative databases that we failed to include. In addition, our ability to examine variable effects across models was limited by model heterogeneity. The inconsistent reporting of c-statistic SE made formal, weighted statistical comparisons between groups of CPMs impossible.

CONCLUSIONS
There is a wide selection of CPMs designed for prognostication following SCA. These models demonstrated excellent ability to discriminate between patients experiencing SCA with good and poor prognosis. The most commonly used predictive variables were initial cardiac rhythm, patient age, and whether
an SCA was witnessed. Discrimination remained high for those models that underwent external validation; however, few CPMs have been rigorously validated, and calibration is rarely reported. Although these quantitative assessments of prognosis may be helpful for decision making on withdrawal of care in arrest survivors, they should be interpreted in the broader context of an individual patient’s overall clinical picture.

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Disclosures
None.

Supplementary Material
Figure S1

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SUPPLEMENTAL MATERIAL
Figure S1. The specific OVID medline search used to collect abstracts for initial screening.

| OVID MedLine Search                                                                 |
|-------------------------------------------------------------------------------------|
| (((predict$ adj1 model$) or (predict$ adj1 instrument$) or (predict$ adj1 score$) or (predict$ adj1 index)).mp. |
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| cardiac arrest/ or exp heart arrest/ or exp sudden death/ or exp cardiopulmonary resuscitation/ or exp cardio-pulmonary resuscitation/ or exp CPR/ or exp ventricular fibrillation/ or exp pulseless ventricular tachycardia/ or exp pulseless electrical activity/ or exp death, sudden/ or exp heart arrest, induced/ |
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