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Primary Stroke Centers Should Be Located Using Maximal Coverage Models for Optimal Access

Enrique C. Leira, MD, MS; Geoffrey Fairchild, MS; Alberto M. Segre, PhD; Gerard Rushton, PhD; Michael T. Froehler, MD, PhD; Philip M. Polgreen, MD, MPH

Background and Purpose—The current self-initiated approach by which hospitals acquire Primary Stroke Center (PSC) certification provides insufficient coverage for large areas of the United States. An alternative, directed, algorithmic approach to determine near optimal locations of PSCs would be justified if it significantly improves coverage.

Methods—Using geographic location–allocation modeling techniques, we developed a universal web-based calculator for selecting near optimal PSC locations designed to maximize the population coverage in any state. We analyzed the current PSC network population coverage in Iowa and compared it with the coverage that would exist if a maximal coverage model had instead been used to place those centers. We then estimated the expected gains in population coverage if additional PSCs follow the current self-initiated model and compared it against the more efficient coverage expected by use of a maximal coverage model to select additional locations.

Results—The existing 12 self-initiated PSCs in Iowa cover 37% of the population, assuming a time–distance radius of 30 minutes. The current population coverage would have been 47.5% if those 12 PSCs had been located using a maximal coverage model. With the current self-initiated approach, 54 additional PSCs on average will be needed to improve coverage to 75% of the population. Conversely, only 31 additional PSCs would be needed to achieve the same degree of population coverage if a maximal coverage model is used.

Conclusion—Given the substantial gain in population access to adequate acute stroke care, it appears justified to direct the location of additional PSCs or recombinant tissue-type plasminogen activator-capable hospitals through a maximal coverage model algorithmic approach. (*Stroke*. 2012;43:2417-2422.)

Key Words: acute stroke ■ economics ■ emergency medicine ■ health policy ■ stroke delivery

Outcomes in ischemic stroke depend on both the timely delivery of thrombolytic therapy¹ and the quality of the ancillary care provided.² A hospital that can provide adequate stabilization and treatment with recombinant tissue-type plasminogen activator, with or without a dedicated stroke unit, may be certified as a Primary Stroke Center (PSC). This certification is a bottom-up voluntary process initiated by interested hospitals. Unfortunately, this self-initiated approach results in insufficient access to PSCs for a large segment of the American population.³ This is particularly dramatic for nonurban areas.⁴ Clearly, additional PSCs are needed to expand the timely access to emergent stroke care for a more reasonable fraction of the population.⁵ However, before this shortage can be addressed, it is important to recognize the magnitude of the associated societal cost and any possible approaches that can be made to minimize the cost. Should the process of further PSC certification continue in this bottom-up self-initiated manner or should an overseeing entity promote and/or direct the placement of additional PSCs?

A top-down directed process could be justified if the number of additional centers required is large or if the directed process significantly increases coverage over the self-initiated process. In this study, we aim to address this question by comparing present and projected PSC population coverage in a traditionally rural state with dispersed population and resources using geographic location–allocation modeling techniques.

Materials and Methods

We first identified all the current PSCs in the state of Iowa. Using the 2009 American Hospital Association's Annual Service Database, we determined all the possible additional PSC locations by identifying hospitals meeting the minimum requirements: the availability of a radiology department with staff available to perform head CT and laboratory services that were available 24 hours a day.^{6,7} We then used a web-based location–allocation calculator of our own design to place PSCs in Iowa. The population in each ZIP code tabulation area (ZCTA) in Iowa was obtained from the 2010 US Census. Figure 1 presents a heat map of the population density of the state of Iowa. Note that we concentrate the entire population of a ZCTA at its geographic centroid.^{8,9}

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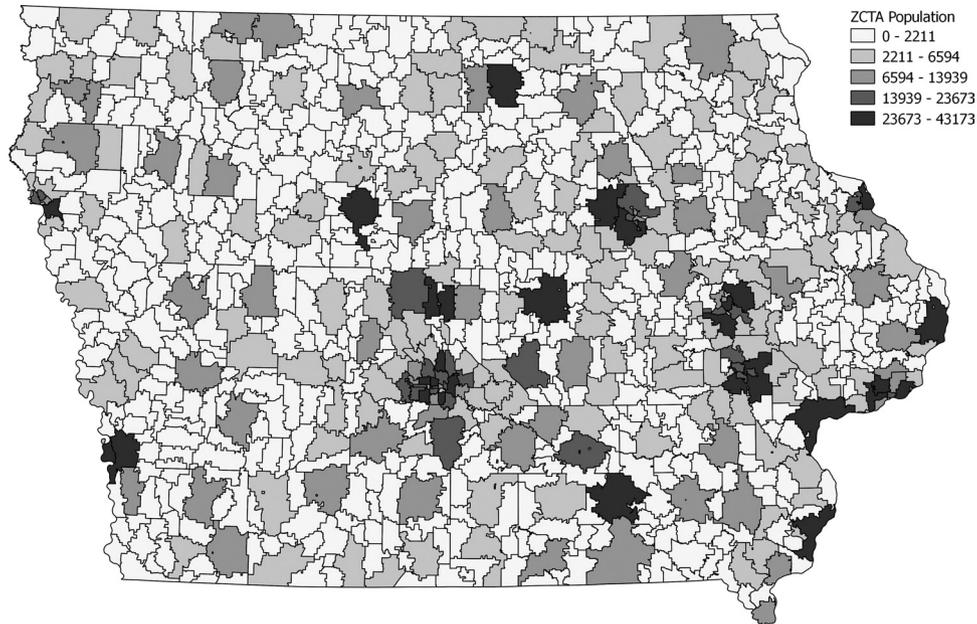


Figure 1. Population distribution of the 935 ZIP code tabulation areas (ZCTAs) in Iowa. The total population of Iowa is 3 047 914. Lighter colors indicate smaller population ZCTAs, whereas darker colors indicate higher population ZCTAs.

The maximal coverage model (MCM) is a commonly used location-allocation model in geographic information systems, which selects facilities that maximize the population contained inside some fixed radius of coverage.¹⁰ This method is used by commercial entities, industries, and business organizations to determine appropriate locations for facilities, including health facilities.¹¹ In this article, we aim to maximize the number of residents in the state that are within a fixed prespecified time-distance, S , of at least one of the N possible PSC sites. This problem is equivalent to minimizing the uncovered population (ie, population further than S from any of the N sites); this formulation makes for a more straightforward mathematical expression¹⁰:

Minimize:

$$\sum_{i=1}^N S_i$$

Subject to:

$$\sum_{j=1}^M w_j \prod_{i=1}^N (1 - s_i y_{ij}) \leq \tau$$

where N is the number of possible treatment sites, M is the number of ZCTAs in Iowa, w_j is the weight of ZCTA j (eg, number of people in that ZCTA), s_i is the selection variable (with value 1 if site i is selected and 0 otherwise), and y_{ij} is the coverage variable (with value 1 if ZCTA j is serviced by a possible site i and 0 otherwise). The constraint sums the w_j values of every ZCTA left uncovered by selected sites, and τ is the number of people we are willing to leave uncovered. When appropriate input values are specified for N , M , τ , w_j (for $j=1 \dots M$), and y_{ij} (for $i=1 \dots N$; $j=1 \dots M$), an algorithmic solution would find values for each s_{ij} , indicating the values sites selected from possible sites constitute a locally optimal configuration. Because the problem is nondeterministic polynomial-time hard (NP-hard; ie, it is infeasible to obtain the optimal solution efficiently), we implemented a greedy approximation algorithm that provides a $\left(1 - \frac{1}{e}\right)$ approximation of the optimal solution.¹² To find the best PSC locations, we first construct a matrix of inter-ZCTA time-distances between ZCTA centroids. Although we could use the great-circle distance formula (ie, geodesic distance and the surface of a sphere) to approximate road distance,¹³ we

instead created a time-distance matrix using Microsoft's Bing Maps API so that our measurements of travel time are as accurate as possible. Next, we repeatedly selected additional treatment sites, each time adding sites that maximize population coverage within time-distance S . The model stops when either (1) we have selected the prespecified number of locations; or (2) we have exceeded the prespecified coverage threshold. The web-based calculator was implemented in Java and PHP.

This calculator was used to estimate the current PSC population coverage in the state of Iowa with 3 different maximum time-distance thresholds (15, 30, and 45 minutes). We then used the calculator to estimate what the hypothetical coverage would be if a MCM had been used to establish the best location for the current number of centers. We also plotted the number of additional PSCs that would be needed to improve the population coverage to a prespecified threshold. We compared the future improvement in coverage among 4 different approaches: (1) a random selection approach (ie, new PSC sites selected uniformly at random); (2) a weighted-random selection approach that mimics the current tendency of PSCs that favor larger hospitals (ie, sites are selected randomly where the probability of selection is weighted by the population contained within time-distance units of a site independent of the presence of other PSCs); (3) a MCM that builds on the existing 12 PSCs; and (4) a hypothetical MCM that was started de novo (ie, without the existing PSCs).

Results

Of the 126 hospitals in Iowa, 120 have the minimum resources required to become a PSC and were included in the analysis. Of those 120 hospitals, 12 (10%) are already PSCs certified through the self-initiation process. The 12 current PSCs, which are located in the largest cities within the state, serve 37.2% of the Iowa population, assuming a time-distance radius of 30 minutes (these same 12 sites cover 21.3% and 60.0% of the population for time-distance radii of 15 and 45 minutes, respectively). The amount of effort that would be required to significantly expand the current coverage of PSCs in Iowa using the MCM is illustrated in Figure 2. Thirty-one additional MCM-placed PSCs (dark gray) would be required to augment the 12 existing PSCs (light gray) to cover

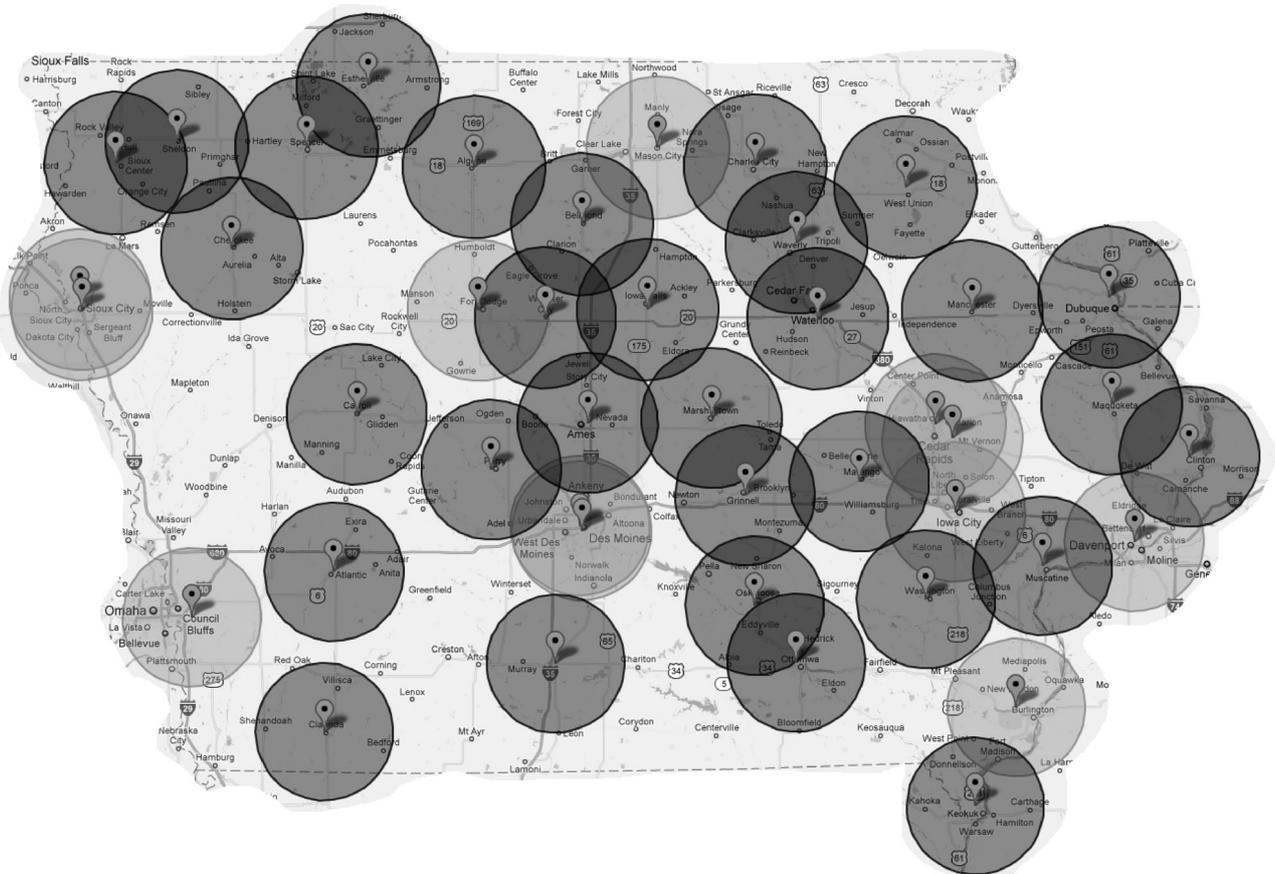


Figure 2. Results of a maximum coverage algorithm showing the location of the additional 31 Primary Stroke Centers (PSCs; dark gray circles) that would be required to cover 75% of the population of Iowa with an assumed 30-minute time–distance radius. The existing 12 PSCs are shown in lighter gray circles. Circles with 20-mile radii are shown around each PSC for visualization purposes.

75% of the population of Iowa with an assumed 30-minute time–distance radius of coverage. Figure 3A through 3C show the relationship between the number of additional MCM-placed PSCs needed and the fraction of the population that would be covered for 3 different time–distance radii of coverage (15, 30, and 45 minutes, respectively). In these 3 graphs, calculations were plotted for the 4 different approaches discussed. To generate curves for the 2 random approaches, we averaged the results from 500 replicates.

The lack of efficiency of the current self-initiated approach is clearly evidenced by showing that 47.5% of the population could be covered presently within a 30-minute radius had a MCM been used to place the first 12 PSCs. Furthermore, future prediction of coverage using the weighted-random selection model to simulate self-initiation in denser population regions shows that 54 additional PSCs would be needed to cover 75% of the population with a 30-minute radius of coverage, whereas only an additional 31 MCM-placed PSCs would be needed to achieve the same degree of population coverage (Figures 2 and 3B).

Discussion

The initiative to certify hospitals as PSC by the Joint Commission or by state health departments is an important step in improving stroke care for Americans.¹⁴ Unfortunately, the current system of self-initiation by willing hospitals

results in sparse coverage for large areas of the population, particularly in rural states. We have confirmed that the overall percentage of the state population adequately covered by PSCs is minimal, which highlights the critical need to increase the numbers of available centers. Although reasonable coverage exists in urban centers of Iowa, the majority of the state’s less densely populated areas has insufficient availability. This reflects the national tendency for larger urban hospitals, typically with an attached stroke unit, to seek PSC certification from the Joint Commission (http://www.jointcommission.org/certification/primary_stroke_centers.aspx). This trend is at odds with the initial intentions of the PSC initiative to certify hospitals that are able to adequately stabilize and initially treat patients with stroke similar to the trauma model.⁶ It might also reflect a tendency for PSC to cluster in a single location due to local competition, a phenomenon described for other critical facilities such as intensive care units.¹⁵ The geographic disparity in access to stroke care for a large proportion of the US population can only increase the existing disparity of stroke care between rural and urban areas.¹⁶ Unfortunately, it is clear that the number of PSCs needed to improve the coverage to acceptable levels is quite large.

We recognize that our findings may, at first glance, give the impression of a self-fulfilling prophecy. After all, it should not be a surprise that a MCM produces better results than random selection. However, the importance of these

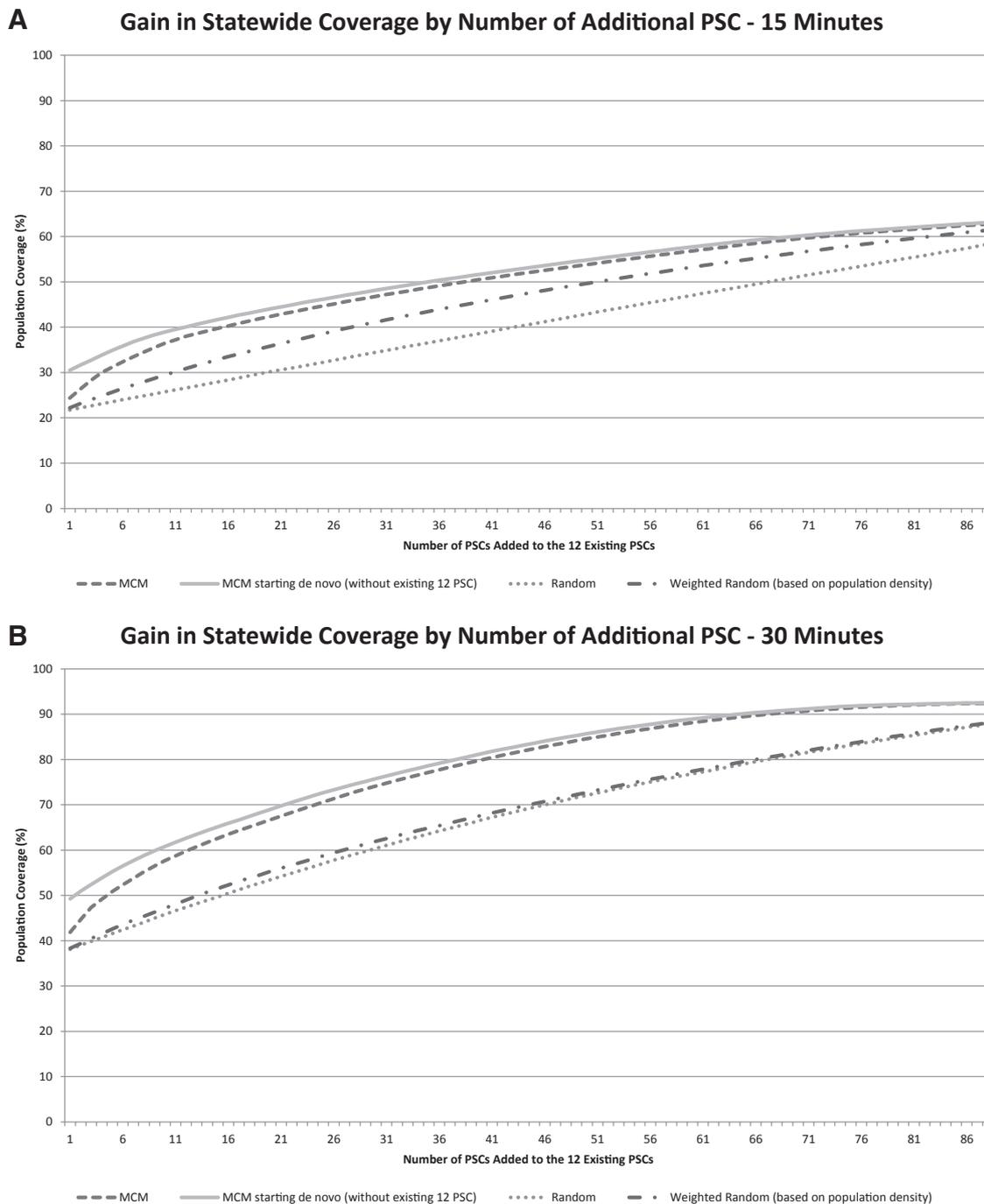


Figure 3. A–C, Projected population coverage as new Primary Stroke Centers (PSCs) are added to the 12 existing PSCs. The dotted line represents a random selection model where sites are selected uniformly at random. The dotted/dashed line represents a weighted-random selection model, which simulates the current self-initiation approach by randomly selecting PSCs with probability proportional to the population contained in each site's radius of coverage. Results garnered from both random selection models were averaged >500 replicates. The dashed line represents a maximal coverage model (MCM) that builds on the existing 12 PSCs. The continuous line represents a hypothetical MCM that was started de novo (ie, without the existing PSCs). Results are shown for 3 different time-distance radii (15, 30, and 45 minutes).

findings lies in quantifying the benefit over the current self-initiated approach. We were surprised to learn how inefficient the current self-initiated model of PSCs is to provide population coverage. We realize that in practice, the process of self-initiation is not entirely random. Larger hospitals providing care to denser areas of populations are more likely to seek PSC certification, so our weighted-random approach was designed to test this real-case scenario.

Still, the difference with a MCM is significant. The existing PSCs in the state of Iowa are not in the most efficient locations to best serve the population. Because this certification has already been accomplished (and we are by no means advocating the removal of the PSC status for any existing center), we present these findings to improve PSC growth in the future. The ratio between minimal coverage and expenses required should be established based on the available resources. However, it is

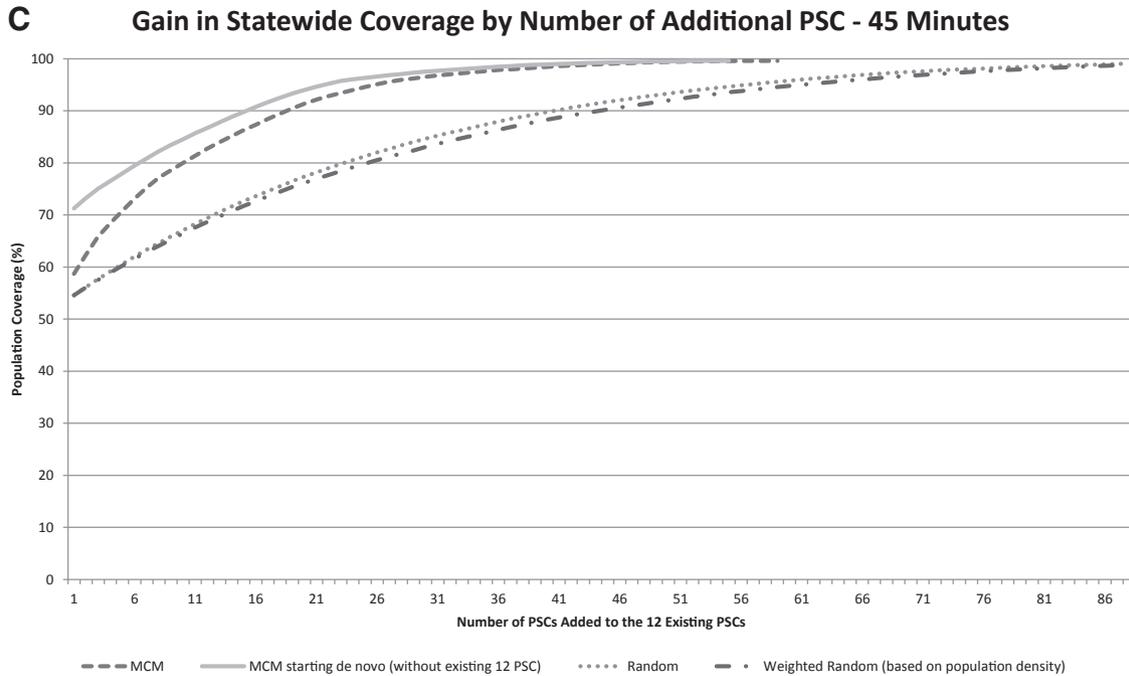


Figure 3 (Continued).

clear that no matter what the parameters are determined to be, a MCM would result in fewer required PSCs and, as a result, lower societal investment. In other words, like in any other resource-limited situation, it is crucial to maximize coverage at the same time as minimizing the resources required.

These results raise the ethical and political question of whether the location of future PSCs should be regulated given the important health implications of receiving timely acute stroke care. We believe these findings will be useful to both government-run healthcare systems and private hospital systems. Governmental operations could stratify their resources to mandate the establishment of PSCs in hospitals located in the most efficient sites. However, this would also be true for privately owned hospital networks that seek to find the ideal location for a PSC within their system based on population distribution. We recognize that a MCM approach would be more difficult to enforce in the private market of small autonomous institutions. In those cases, rather than mandating a location, a MCM could be used by a state institution to decide how many additional centers are needed and in which hospitals they should concentrate educational efforts and incentives to promote PSC certification.¹⁷ A MCM would be the basis for a rational justification by location that can be used to incentivize the process in smaller institutions. This approach might also be useful for other acute stroke care applications such as to find the best locations for remote centers for telemedicine networks by identifying recombinant tissue-type plasminogen activator-ready hospitals as key steps in the regionalization process,¹⁸ or identifying the best centers for a spoke-and-hub comprehensive stroke center network.¹⁹ Geographic computerized methods that find the best location to improve access have been proposed for other services such as nephrology services²⁰ or flu surveillance.¹¹ We have made our maximal coverage calculator web-based to allow the system to

be used by other states to determine the best locations of PSCs (<http://compepi.cs.uiowa.edu/~gcfairch/sentinel>). The user enters any ZIP codes in which a PSC currently exists, ZIP codes in which candidate PSCs exist, the number of candidate PSCs to find, and the radius of coverage of each PSC.

We recognize that there might be resistance to further increase in the number of PSCs. Barriers to this process have already been identified.²¹ Because of initial self-selection by larger hospitals, any further expansion of the number of PSCs in rural states becomes the burden of the remaining smaller hospitals. Being a small hospital is not per se an impediment for a PSC designation.²² In fact, most small rural hospitals have adequate resources to become PSCs, suggesting that such certification could be achieved with adequate administrative and financial support.⁷ However, it might be difficult to interest additional smaller hospitals in pursuing PSC certification, particularly when they did not volunteer for the process in the years since the PSC initiative has been available. We recognize that becoming a PSC is an expensive and onerous process for small hospitals. For that reason, we propose a central planning incentive to subsidize these costs for critical locations. Alternatively, in cases in which optimal locations prove to be infeasible for financial or other reasons, the same methodology can be used to identify second-best locations and the cost incurred in selecting the second best. We hypothesize that institutions in critical uncovered geographical locations might respond to statewide or national incentives to become a PSC.

There are limitations to this research. We recognize that the choice of using PSCs might underestimate the state stroke treatment capabilities because there are hospitals that can give recombinant tissue-type plasminogen activator without being certified as a PSC. We used the current PSC certification to test the optimization model because it is a rigorous

initiative widely accepted by the stroke community nationwide as a standard of acute stroke care. Also, there could be uncertainty about what constitutes a “statewide significant” difference in population coverage. This is analogous to the dilemma between statistical significance and clinical significance. Currently, 10% of the population of the state of Iowa (3 046 355 according to the US Census Bureau 2010) represents 304 635 persons. That means that if the current PSCs had been placed using a MCM, an additional 300 000 individuals would have adequate PSC coverage. Again, that is without any additional societal investment, only by locating the PSCs at the most efficient locations. We judge this number to be significant and meaningful for stroke care at a statewide level. Another limitation is the predictive nature of the model. We have minimized that uncertainty by testing a weighted-random approach that approximates the current process to become a PSC.

There are also operational and implementation limitations to this research. Because ZCTA boundaries are not ZIP code boundaries, we assume that the population is concentrated at the center of the ZCTA. However, although this limitation could affect the magnitude of the effect, it does not affect the outcomes of this model nor the conclusions. We also recognize that there are potential limitations to generalize these results to other states that may have different patterns of population density and resource dispersion; we have used for this research a state that is a moderate example of dispersion for a rural population within the United States.

In summary, the process of becoming a PSC has been one driven by self-initiation. However, this approach is in sharp contrast to the systematic planning that normally occurs for other important societal services and has resulted in insufficient access to stroke centers for large segments of the US population. Expanding the number of PSCs is clearly necessary, and such an expansion will likely benefit from the efficiency of directed optimization models. Lastly, and more importantly, such methods would result in minimization of societal investment at the same time as assuring some measure of maximal use.

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Disclosures

None.

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