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ORIGINAL RESEARCH

Prehospital-Stroke-Scale Parameterized Hospital Selection Protocol for Suspected Stroke Patients Considering Door-to-Treatment Durations

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BACKGROUND: To mitigate uncertainty that may arise in the judgment of emergency medical technicians when relying on a prehospital stroke scale at the scene, we propose a hospital selection protocol that considers the uncertainty of a prehospital stroke scale and the actual door-to-treatment durations, and we have developed a web-based system to be used with mobile devices.

METHODS AND RESULTS: This hospital selection protocol incorporates real-time, estimated transport time obtained from Google Maps, historical median door-to-treatment duration at hospitals that only provide the standard intravenous thrombolysis treatment, and at hospitals with endovascular thrombectomy for probable large-vessel occlusion cases. We have validated the efficiency of the proposed protocol and compared it with other strategies used by emergency medical technicians when deciding on a receiving hospital. Using the proposed protocol for the triage reduces the time from onset to receiving definitive treatment by nearly 11 minutes. We found that the nearest endovascular thrombectomy–capable hospital from the scene may not be the most ideal if the door-to-treatment durations are discriminative. The results show that, when the tolerable bypass transport threshold and administration time are reduced to 9 minutes and 30.5 minutes, respectively, 228 patients out of 7678 cases, whose receiving hospitals were changed to endovascular thrombectomy–capable hospitals, received definitive treatment in a shorter time. The results of our analysis give recommendations for appropriate allowable bypass transport time for regional planning.

CONCLUSIONS: By applying almost-real value parameters, we have validated a web-based model, which can be universally adapted for optimal, time-saving hospital selection for patients with stroke.

Key Words: emergency medical service ■ hospital selection protocol ■ large vessel occlusion ■ stroke

Patients experiencing acute ischemic stroke (AIS) have better outcomes if the time is reduced between onset and receiving definitive treatment, such as intravenous thrombolysis (IVT) or endovascular thrombectomy (EVT), to reperfuse the brain tissues.[1–7] There are already strategies designed to ensure that patients with AIS receive definitive treatment as quickly as possible. However, it is sometimes difficult for emergency medical technicians (EMTs) to determine the best approach when evaluating a patient because procedural uncertainties (such as transport time, door-to-treatment duration, and testing, etc.) have to be considered. EMTs commonly reference prehospital stroke scales to identify patients with large vessel occlusion

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CLINICAL PERSPECTIVE

What Is New?

- Incorporating the Mathematical Programming and Geographic Information System, we propose a protocol to decide which hospital a patient suspected of experiencing stroke should be sent to.
- The protocol, a web-based system, accessible via the mobile devices of prehospital personnel, has been developed. The prehospital personnel will be able to use this system at the scene and make timely decisions.

What Are the Clinical Implications?

- Aided by the web-based system, the prehospital personnel can make more appropriate decisions for patients.
- A reasonable bypass strategy can allow patients to receive treatment faster for better prognosis with this system.

Nonstandard Abbreviations and Acronyms

AIS	acute ischemic stroke
CPSS	Cincinnati Prehospital Stroke Scale
EVT	endovascular thrombectomy
IVT	intravenous thrombolysis
LVO	large vessel occlusion
rt-PA	recombinant tissue plasminogen activator

(LVO) and determine the receiving hospital accordingly. However, these scales are not 100% accurate in identifying LVO. Some patients with LVO may be sent to a hospital that only provides IVT. They then have to be transferred to an EVT-capable hospital, after tests, which delay their receiving treatment.

Every time interval that a patient has to undergo before receiving definitive treatment must be carefully calculated. Real-time transport time is often discussed in the literature. For time intervals, after a patient has arrived at the first receiving hospital, Schlemm et al[8] considered the door-to-treatment duration based on the American Heart Association [8–13] guidelines, while other researchers used the data of door-to-treatment duration in clinical trials,[13] or based on systems of care recommendations.[14] Actual door-to-treatment duration in hospitals is rarely discussed in the literature.

The aim of developing hospital selection protocol is to provide advice and to help EMTs make a reasoned decision. Before the introduction and implementation of the prehospital-stroke-scale parameterized hospital selection protocol, EMTs would send a patient to the closest hospital in time or distance from the scene. However, existing models do not factor in the differences in the procedures needed by patients with stroke because of the uncertainties that arise when assessing the severity of the stroke using the prehospital stroke scales.

We propose a hospital selection protocol with a probability measure to identify patients with LVO according to the number of the prehospital stroke scale indicators presented, which other mathematical models have not considered. Furthermore, the method is guaranteed to minimize the expected time for a patient to receive definitive treatment. The protocol, a web-based system,[15] accessible via the EMTs' mobile devices, has been developed for Taipei City. EMTs will be able to use this system at the scene and make timely decisions.

METHODS

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

Study Setting

To carry out the study, we considered a capital city where the average stroke incidence rate is 330 per 100 000 people, of which 74% are ischemic stroke cases. The city has a metropolitan area of 272 km^2. It has a population of 2.65 million with an inflow working population of 3 million. The 2-tier fire-based emergency medical service (EMS) system contains 41 basic life support units and 4 advanced life support units. In the city, the EMS helps to transport ≈30% of patients with stroke to a hospital. There are currently 1206 EMTs in the city, who at the scene, use the Cincinnati Prehospital Stroke Scale (CPSS) to identify patients with acute stroke. The symptoms of CPSS included the following presentations: facial palsy, arm weakness, and speech abnormalities.[16] In addition, they do the pinprick test to check blood glucose levels. There are ten 24/7 hospitals in the city that provide recombinant tissue plasminogen activator (rt-PA) 24/7, of which 6 are also EVT-capable.

One-Stage Stochastic Optimization Model

In the proposed hospital selection protocol, we use a 1-stage stochastic optimization model,[17] where the decision variable at the scene is the receiving hospital for a patient, while the random variable is the time taken for the patient to receive definitive treatment. The probability measure to identify patients with LVO, according to the number of CPSS symptoms presented, is used to calculate the minimized expected time for the patient to receive definitive treatment because we cannot know exactly the patient's stroke level before obtaining the results of computed tomography angiography of the brain.

We can obtain 2 meaningful quantities from the model output: the expected time in which a patient will receive definitive treatment, and whether a patient should be sent to a hospital only providing IVT followed by possible transfer, or sent directly to an EVT-capable hospital to receive definitive treatment. The sequential process before a patient receives definitive treatment, and the 2 treatment or transfer scenarios are all taken into account (Figure 1).

Let p_i be the probability that patient i is experiencing an AIS without LVO according to the number of CPSS symptoms they have when tested by the EMTs on the scene, and let $1-p_i$ be the probability that patient i has LVO. The probabilities of a patient having LVO, and conditional on 3, 2, or 1 of the 3 CPSS symptoms, are 0.310, 0.265, and 0.239, respectively.[18] There is also an alternative probability measure related to the number of CPSS symptoms, according to Richards et al.[19] Results related to those of Richards et al[19] are shown in Data S1.

Therefore, when a patient is sent to an EVT-capable hospital, the expected time to receive the definitive treatment is $S_i + T_{a,i} + Q_a + p_i D_a + (1-p_i)\overline{D}_a$ with the following definitions:

S_i:	Response time for the ambulance to reach the site of patient i plus on-scene time
$T_{a,i}$:	First transport time from getting patient i on the scene to hospital a
Q_a:	Door-to-test duration in hospital a
D_a:	Test-to-treatment duration in hospital a for a patient who has AIS without LVO
$\overline{D}_a$:	Test-to-treatment duration in hospital a for a patient with LVO

The expected time to receive definitive treatment when a patient is initially sent to a hospital only providing IVT (rt-PA hospital) but who may have to be transferred to an EVT-capable hospital is $S_i + T_{a,i} + Q_a + p_i D_a + (1-p_i)(A+E_a)$ with the following further definitions:

A:	Administration time of hospital transfer
E_a:	The shortest possible time for a patient to be transferred from an rt-PA hospital a to an EVT-capable hospital and to receive definitive treatment, ie, $\min_{b \in \text{set of CSCs}} (\overline{T_{a,b}} + Q_b + \overline{D}_b)$
$\overline{T_{a,b}}$:	The secondary transport time from an rt-PA hospital a to an EVT-capable hospital b

Transfer time E_a includes the driving time from the rt-PA hospital to the nearest EVT-capable hospital and the door-to-treatment duration in the EVT-capable hospital. From the data given, the transport driving time from the patient's address was calculated as off-peak according to Google Maps. Administration time was defined as the time interval from the first image of computed tomography angiography of brain shown on the computer screen to an rt-PA hospital departure. The administration time based on Ng et al[20] was initially set at 46.5 minutes. The door-to-test duration was defined as the time interval from rt-PA hospital arrival to the first image of computed tomography angiography of the brain shown on the computer screen. The door-to-test duration and test-to-treatment duration were set by the medians of the historical data from each hospital in Taipei City, which varied among hospitals.

When the EMT inputs into the web-based system the patient's location and number of CPSS symptoms, whether they have LVO or not, the EMT will only get 1 suggested receiving hospital, which is considered to be the most appropriate. In addition, when the time difference between the scene to any rt-PA hospital and the scene to the nearest EVT-capable hospital is less than U seconds, the model always sends the patient directly to the EVT-capable hospital.

U:	Tolerable bypass transport threshold determined by the manager

U was initially set to 15 minutes because the American Heart Association guidelines suggest that good outcomes deteriorate with every 15-minute delay. The mathematical model is described in Data S1.

The parameters inputted into the model are almost actual data. The transport time is calculated according to off-peak driving time in Google Maps, and the processing time in each hospital is based on the 4-year median data from 2016 to 2019. To test the model's accuracy, we used the 6-year historical data of 7678 patients who had a suspected stroke and who exhibited at least 1 of the 3 CPSS symptoms between January 1, 2010, and December 31, 2015. The model was implemented with A Mathematical Programming Language,[21] which is an intuitive algebraic modeling system, and IBM ILOG CPLEX Optimization Studio,[22] which was used to solve the underlying mathematical programming model. This study and stroke registry were approved by the Institutional Review Board of National Taiwan University Hospital.

Primary Approach of Critical Parameters

We tested the performance of the proposed protocol with a 6-year data set of 7678 histories of patients who have had a suspected stroke in Taipei City. Among the 7678 patients, 4037 had 3 CPSS symptoms, 1319 had 2 symptoms, and 2322 had 1 symptom.

Using the probability measure given by Scheitz et al,[18] we conducted a primary approach of the administration time needed for hospital transfer, and the tolerable bypass transport threshold below which a

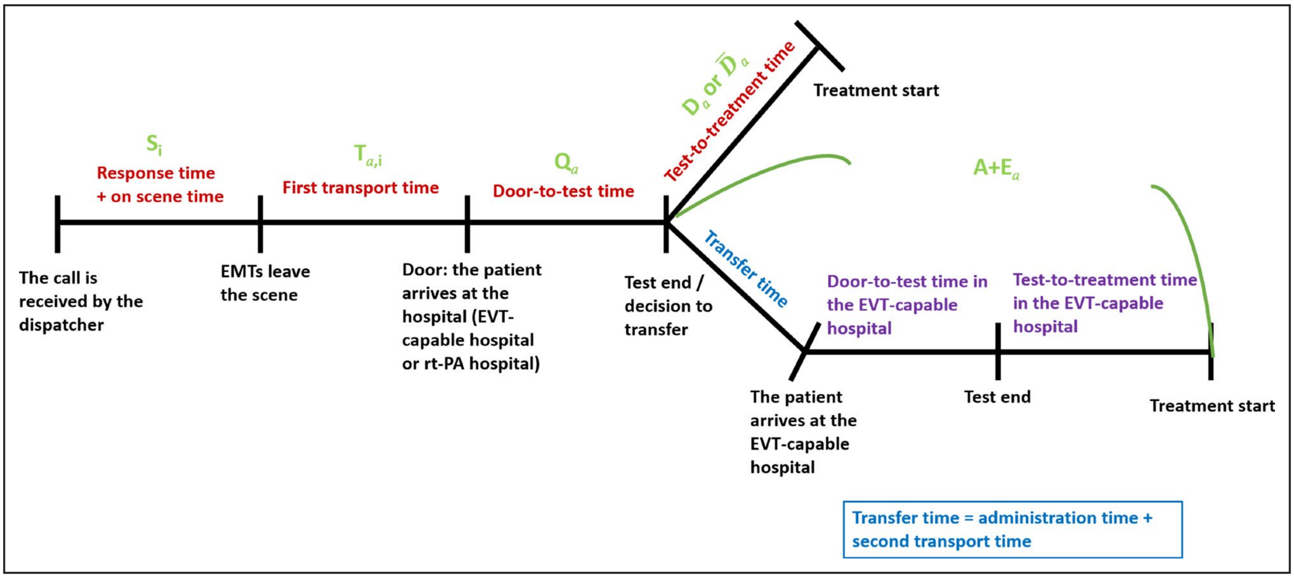

Figure 1. Processes for a patient experiencing acute ischemic stroke to receive definitive treatment.
EVT-capable hospital, providing both intravenous thrombolysis and endovascular thrombectomy; rt-PA hospital, providing only intravenous thrombolysis. EMTs indicates emergency medical technicians; EVT, endovascular thrombectomy; and rt-PA, recombinant tissue plasminogen activator.

patient bypasses the nearer hospital providing IVT to go straight to an EVT-capable hospital.

We then decreased the initial parameters of the tolerable bypass transport threshold *U* of 15 minutes and administration time *A* of 46.5 minutes by 1 minute at a time. From the results of the analysis, we selected 3 critical combinations of values. The first is when patients are sent to rt-PA hospitals to begin with (as opposed to all patients being sent directly to EVT-capable hospitals). The second and third critical combinations, when decreasing the 2 parameters, show significant changes in the total expected time for a patient to receive definitive treatment. Potentially, setting 1 of these 2 critical combinations of values of *U* and *A* as a new practical standard could be more appropriate to Taipei City than the initial (current) values.

Comparisons With Other Strategies for Deciding on a Receiving Hospital

We compared the time to receive definitive treatment when using the proposed hospital selection model with the other 4 strategies. We also generated plots to validate the efficiency of the proposed protocol under different situational parameters. We can thus suggest future applications of the proposed strategy. The following are the 5 strategies we compared for sending patients with AIS to a hospital:

1. A patient with a suspected stroke with at least 1 CPSS symptom is sent to the nearest hospital, whether it is EVT-capable or rt-PA-capable. If a patient with LVO is sent to an rt-PA-capable hospital, the patient should be transferred to the nearest EVT-capable hospital.
2. A patient with a suspected stroke with at least 1 CPSS symptom is sent directly to the nearest EVT-capable hospital.
3. A patient with a suspected stroke with at least 1 CPSS symptom is sent to a hospital according to the result of the proposed hospital selection model (proposed strategy).
4. A patient with a suspected stroke is sent to a hospital based on the number of their CPSS symptoms. If a patient has 3 CPSS symptoms, they are sent directly to the nearest EVT-capable hospital. A patient with 1 or 2 CPSS symptoms is sent to the nearest hospital, whether it is EVT-capable or rt-PA-capable.
5. A patient with a suspected stroke is sent to a hospital based on the number of their CPSS symptoms. If a patient has 2 or 3 CPSS symptoms, they are sent directly to an EVT-capable hospital. If a patient has 1 CPSS symptom they are sent to the nearest hospital, whether EVT-capable or rt-PA-capable.

The information in our historical data only gives each patient's number of CPSS symptoms. It does not include whether or not a patient had confirmed LVO. To evaluate the performances of the above 5 strategies, we simulate the distributions of the 2 classes of patients with stroke, AIS with LVO and AIS without LVO, using the following sampling method where we adopt the probability that a patient is LVO, conditional on their number of CPSS symptoms; and we randomly extract patient data and assume their confirmed diagnosis:

Random sampling method: In our 2010 to 2015 historical data, there were 4037 people with 3 CPSS symptoms, and the probability of LVO in this group was 0.31 based on estimations by Scheitz et al[18]; that is, 31%, or 1251 out of 4037 patients were estimated to have had LVO. There were 1319 people with 2 CPSS symptoms, and the probability of those patients having LVO was estimated at 0.265: that is, 26.5%, or 350 out of 1319 people. There were 2322 people with 1 CPSS symptom, and the probability of patients having LVO in this group was estimated at 0.239. That is, 23.9% or 555 out of 2322 people. We coded in R to randomly extract patients' data and assumed that these patients had confirmed LVO. Following the Scheitz et al. probability measure,[18] we extracted 1251 patients from those with 3 CPSS symptoms, 350 patients with 2 CPSS symptoms, and 555 patients with 1 CPSS symptom. Thus, 2156 patients were assumed to have LVO, while the other 5522 patients were assumed to be without LVO.

We used the sampling method 5 times to randomly generate 5 different patient profiles for each probability measure. We then simulated the prehospital process under 5 strategies to determine the patients' first receiving hospitals and computed the time for each patient to receive treatment over the 5 profiles. We referred to running 5 strategies on 1 profile as a trial. We ran 5 trials for each probability measure.

RESULTS

With the parameters set at the aforementioned initial values, the simulation of the proposed protocol sends all patients with a suspected stroke directly to an EVT-capable hospital, and 2643 (34.42%) of those bypass the nearest rt-PA hospital. The results of the primary approach show that, when the tolerable bypass transport threshold *U* and administration time *A* are reduced to 14 minutes and 41.5 minutes,, respectively, a few patients are sent to the rt-PA hospitals. When the tolerable bypass transport threshold *U* is 9 minutes and the administration time *A* is 30.5 minutes, the number of patients sent to rt-PA hospitals substantially increases (Figure 2). (The comprehensive results of the numbers of patients sent to an EVT-capable hospital at different tolerable bypass transport thresholds *U*, and administration times *A*, are shown in Table S1. The comprehensive results related to those of Richards et al[19] are shown in Figure S1 and Table S2.) To decrease the time needed for a patient to get definitive treatment, we consider the parameter combination in Taipei City of the tolerable bypass transport threshold *U* set to 9 minutes, and administration time *A* set to 30.5 minutes. With these settings, 228 patients are initially sent to the rt-PA hospitals, and the overall time reduction for the 7678 patients is 767.8 minutes. That is, the 228 patients sent to rt-PA hospitals can receive definitive treatment an average of 3.3 minutes faster, although they may need more time, such as transfer time, administration time,

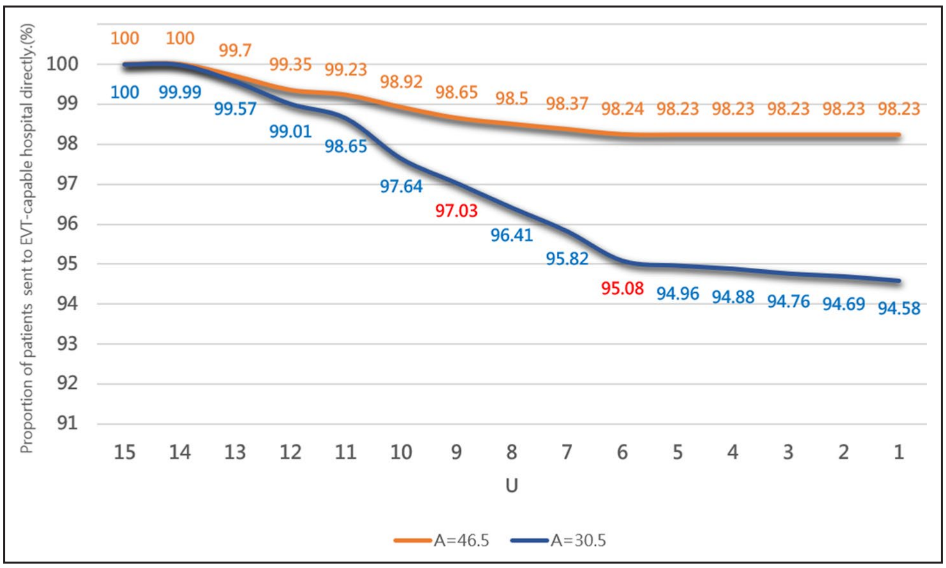

Figure 2. Number of patients sent directly to an EVT-capable hospital at different values of *U* for *A*=46.5 and 30.5 minutes.

U (minute): the time difference between the scene to any rt-PA hospital and the scene to the nearest EVT-capable hospital. A (minute): the time interval from the first image of CT angiography of brain shown on the computer screen to an rt-PA hospital departure. CT indicates computed tomography; EVT, endovascular thrombectomy; and rt-PA, recombinant tissue plasminogen activator.

Table 1. Primary Approach for Adjusting Threshold *U* and Administration Time *A* when the Probabilities of a Patient With Large Vessel Occlusion Showing 1, 2, or 3 Symptoms of the Cincinnati Prehospital Stroke Scale are 0.239, 0.265, and 0.310, Respectively

Tolerable bypass transport threshold *U* (min)	Administration time *A* (min)	Number of patients sent to rt-PA hospitals first	Number of patients sent directly to EVT-capable hospitals	Expected time that patients receive definitive treatment (min)
15	46.5	0	7678	101.78
9	30.5	228	7450	101.68
6	30.5	378	7300	101.63

EVT-capable hospital, providing intravenous thrombolysis and endovascular thrombectomy; rt-PA hospital, providing only intravenous thrombolysis. EVT indicates endovascular thrombectomy; and rt-PA, recombinant tissue plasminogen activator.

and 1 more door-to-test duration, than a patient sent directly to an EVT-capable hospital.

To balance the provision of medical resources in Taipei City, we consider the parameter combination of *U* set to 6 minutes and *A* set to 30.5 minutes. With these settings, 378 patients are sent to rt-PA hospitals according to the proposed model. Compared with the results where *U* is 9 minutes with the same *A*, these 378 patients can only reduce their time by 3 minutes before receiving definitive treatment, as an additional 150 patients are initially sent to the rt-PA hospitals to mitigate congestion in EVT-capable hospitals (Table 1). The results related to those of Richards et al[19] are shown in Table S3.

According to the results shown in Table 2, when we used strategy c to determine the receiving hospital, the patients received definitive treatment in the shortest time. Although strategy c sends all patients to EVT-capable hospitals, which has the same outcome as strategy b with the initial parameters, strategy c saves each patient ≈12 minutes before receiving definitive treatment. This difference is because, in strategy b, some patients are sent to an EVT-capable hospital that is not the nearest one and strategy c benefits from a shorter door-to-treatment duration. In Table 3, all 6 EVT-capable hospitals can receive patients with strategy b. With strategy c, however, patients are sent only to 3 EVT-capable hospitals: B1, B2, and B3 (see Figure S2 for the map of the hospital distribution in Taipei City), because strategy c takes into account not only the transport time, but also the discriminative door-to-treatment duration in each hospital. The results related to those of Richards et al[19] are shown in Table S4 and S5.

According to Table 4, when the parameters of the tolerable bypass transport threshold *U* and administration time *A* are 15 minutes and 46.5 minutes, respectively, the average time for a patient to receive definitive treatment taken over 5 trials is 101.7 minutes, which is very close to the expected time of 101.7 minutes estimated by the model. With 2 other sets of parameters, the average times taken over 5 trials are also close to the expected time estimated by the model. This phenomenon occurs because we used the same probability measure to simulate the LVO patient distribution as we did for the model. The results related to those of Richards et al[19] are shown in Table S6.

In the web-based triage system,[15] EMTs must enter all the required information in the form, which includes the patient's background information, current location, and the number of CPSS symptoms, on the "Acute Stroke Patient Information" page. After clicking on the "submit" button, EMTs will see the "The Best Solutions" page. On the "The Best Solutions" page, there are respectively 3 recommended hospitals based on the proposed protocol and the nearest-delivery strategy. The EMTs then decide what hospital the patient will be sent to and will submit the result to the database.

DISCUSSION

Currently, EMTs choose the receiving hospital based on the result of the prehospital stroke scale and the time or distance from the scene to the hospitals. However, basing the decision only on the result of the prehospital stroke scale is insufficient because of the inaccuracy of

Table 2. Mean Time (in Minutes) for a Patient to Receive Definitive Treatment Under the 5 Strategies for Deciding the Receiving Hospital. (*U* = 15, *A* = 46.5. Probability measure, Scheitz et al[18])

	Strategy a	Strategy b	Strategy c	Strategy d	Strategy e
Trial 1	111.92	113.38	101.77	112.43	112.78
Trial 2	111.67	113.22	101.75	112.20	112.50
Trial 3	111.90	113.38	101.77	112.40	112.73
Trial 4	112.35	113.72	101.90	112.87	113.07
Trial 5	111.80	113.38	101.77	112.42	112.65
Average	111.93	113.42	101.79	112.46	112.75

Table 3. Number of Patients Sent to Each Receiving EVT-Capable Hospitals for Strategies b and c. B1-B6 Refer to the 6 EVT-Capable Hospitals. (*U* = 15, *A* = 46.5. Probability Measure, Scheitz et al[18])

	B1	B2	B3	B4	B5	B6
Strategy b	983	2104	836	1234	1397	1124
Strategy c	80	5277	2321	0	0	0

EVT indicates endovascular thrombectomy.

the prehospital stroke scales. To improve the accuracy of the decision and to minimize the time for a patient to receive definitive treatment, and in addition to the variables used by the EMTs, discriminative door-to-treatment duration in each hospital and transfer time between hospitals should be considered. The results of our model show that the optimality of a receiving hospital could be significantly affected because the door-to-treatment duration in the 6 EVT-capable hospitals in Taipei City are quite varied, with the difference between the shortest door-to-treatment duration and the longest door-to-treatment being ≈1 hour. As a result, if a patient is sent to an EVT-capable hospital with a longer door-to-treatment duration, it may take more time for them to receive definitive treatment than being sent to an EVT-capable hospital further away, but with a shorter door-to-treatment duration.

There have been many studies that discuss prehospital triage for patients with acute stroke; however, few of them detail the in-hospital time. Since the question of whether or not a patient has LVO can only be determined after a hospital test, we take into consideration the probability of a patient having LVO, discuss the possible hospital treatment needed, and calculate the total expected time, which is an important complementary factor in the triage strategy, and not fully addressed in previous research. This additional information gives EMTs a more comprehensive model to work with when making decisions.

The simulation results show that the hospitals providing stroke treatments in Taipei City are sufficient in number and are geographically close to each other. So the difference in transport times between the scene to the nearest rt-PA hospital and the scene to any EVT-capable hospital is rarely >15 minutes, which coincidentally makes these results seem to recommend sending a patient directly to an EVT-capable hospital. If the proposed model is used in different regions, there will be no such results because of the special circumstances of Taipei City. Administration time *A* for hospital transfer also impacts the results. The shorter the transfer time, the more patients with suspected LVO can tolerate being sent initially to an rt-PA hospital and then transferred before receiving definitive treatment.

In the simulation, the proposed model (strategy c) has the shortest time for a patient to receive definitive treatment when compared with 4 typical strategies. Although no patients are sent to rt-PA hospitals when using the model with the initial parameters, the time to get definitive treatment is shorter than the results of strategy b, which is to send patients directly to the nearest EVT-capable hospital. Regarding whether patients can be assigned to rt-PA hospitals to balance the use of medical resources and to mitigate the potential crowding in EVT-capable hospitals, we found that shortening the administration time for hospital transfer can resolve the problem. Moreover, if the administration time for transfer is improved to the intended level according to our primary approach, patients in some locations can initially be sent to rt-PA hospitals and still receive definitive treatment in a shorter expected time.

This model and the web-based system[15] can be applied to other regions and countries based on the preliminary experiments and validation in this work for Taipei City. The parameters of hospitals should be updated according to the historical data for hospitals in the target region. The tolerable bypass transport threshold *U* and administration time *A* should be adjusted according to a primary approach based on patients' data in the target region. We believe that the model can help EMTs determine suitable receiving hospitals and that patients can receive definitive treatment in the shortest time. Obtaining an optimal solution to the underlying mathematical model can be done on Microsoft Excel, but using A Mathematical Programming Language[21] and CPLEX,[22] as we did here, ensures the shortest computation time.

Limitations

In our study, the model was tested using 2010 to 2015 historical patient data, and the parameters were set based on historical median durations. The period of patient data

Table 4. Mean Time for a Patient to Receive Definitive Treatment for the 5 Trials. (Probability Measure, Scheitz et al[18])

Tolerable bypass transport threshold *U* (min)	Administration time *A* (min)	Expected time for a patient to receive definitive treatment (min)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
15	46.5	101.78	101.77	101.75	101.77	101.90	101.78
9	30.5	101.68	101.65	101.72	101.68	101.88	101.68
6	30.5	101.63	101.68	101.72	101.73	102.00	101.63

was before the major randomized control trials showing a benefit with EVT.[4–6,23,24] However, these data and averages will gradually change. To ensure the method's effectiveness, the model's parameters should be adjusted periodically according to the latest information.

In addition, the model would output different optimal hospitals under different probability measures. Although we examined 2 probability measures, it requires further research to know whether these are close to the true probability measure for other regions, seasons, and races. Increasing the accuracy of the probability measure for the target region would improve the model and reduce the time for a patient to receive definitive treatment.

Finally, in our study, tolerable bypass transport threshold U was initially set to 15 minutes and then was shortened for primary approach. The tolerable bypass transport threshold was suggested to be 30 minutes in recent recommendations in 2021,[25] and it seemed that the initial threshold in our study was shorter. However, since the tolerable bypass transport threshold U was initially set to 15 minutes, the simulation of the proposed protocol already sends all patients with a suspected stroke directly to an EVT-capable hospital. It is believed that putting a longer threshold than 15 minutes into the model has the same results if the data in Taipei are used. A tolerable bypass transport threshold may be used up to 30 minutes in future models for different areas.

CONCLUSIONS

We propose an optimization model that considers not only the probability of a patient having LVO and the real-time transport, but also the door-to-treatment duration in hospitals and the transfer time (secondary transport time), and administration time. Our web-based system can help EMTs decide on the most suitable receiving hospital and enable patients with a suspected stroke to receive definitive treatment in the shortest time. The system has a generality that can be applied in other regions and countries.

ARTICLE INFORMATION

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Disclosures

None.

Supplemental Material

Data S1–S2
Tables S1–S6
Figures S1–S2

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SUPPLEMENTAL MATERIAL

Supplemental Methods

Data S1. List of Notations and The Model

The following mathematical notations are defined to establish the hospital selection model. This model aims to ensure that a patient suffering from acute ischemic stroke (AIS) receives definitive treatment within the shortest possible time.

Sets

$\boldsymbol{H}$	Set of hospitals that provide both the rt-PA treatment and the endovascular thrombectomy treatment. (EVT)
$\boldsymbol{C}$	Set of hospitals that provide only the rt-PA treatment
$\boldsymbol{\Omega}$	Set of patients

Parameters

p_i	$i \in \boldsymbol{\Omega}$	The probability that patient i with AIS does not have large vessel occlusion (LVO)
$1 - p_i$	$i \in \boldsymbol{\Omega}$	The probability that patient i has LVO
$T_{a,i}$	$i \in \boldsymbol{\Omega}, a \in \boldsymbol{H} \cup \boldsymbol{C}$	First transport time from getting patient i at the scene to hospital a

$\overline{T_{a,b}}$	$a \in \boldsymbol{C}, b \in \boldsymbol{H}$	The second transport time from rt-PA hospital a to an EVT-capable hospital b
Q_a	$a \in \boldsymbol{H} \cup \boldsymbol{C}$	Door-to-test duration in hospital a
D_a	$a \in \boldsymbol{H} \cup \boldsymbol{C}$	Test-to-treatment duration in hospital a for a patient with AIS without LVO
$\overline{D}_a$	$a \in \boldsymbol{H}$	Test-to-treatment duration in hospital a for patient with LVO
E_a	$a \in \boldsymbol{C}$	The shortest possible time for a patient transferred from hospital a to an EVT-capable hospital to receive definitive treatment, i.e., $\min_{b \in \boldsymbol{H}}(\overline{T_{a,b}} + Q_b + \overline{D}_b)$
A		Administration time of hospital transfer
S_i	$i \in \boldsymbol{\Omega}$	Response time for the ambulance to reach the site of patient i plus on-scene time
U		Tolerable bypass transport threshold determined by the manager (if the transport time difference between the scene to the nearest rt-PA hospital and the scene to the nearest EVT-capable hospital is not more than U seconds, then bypass the nearest rt-PA hospital to the nearest EVT-capable hospital)
M		A large number

Variables:

$X_{a,i}$	$i \in \boldsymbol{\Omega}, a \in \boldsymbol{H} \cup \boldsymbol{C}$	1 if patient i is sent to hospital a from the scene; 0 otherwise.

$$\textbf{Minimize} \sum_{a \in \boldsymbol{H}} (S_i + T_{a,i} + \ Q_a \ + p_i \ D_a + (1 - p_i)\overline{D}_a)X_{a,i}$$

$$+ \sum_{a \in \boldsymbol{C}} (S_i + T_{a,i} + \ Q_a \ + \ p_i D_a + (1 - p_i)(\ A + \ E_a))X_{a,i} \quad (1)$$

Subject to

$$\sum_{a \in \boldsymbol{H} \cup \boldsymbol{C}} X_{a,i} = 1 \quad (2)$$

$$\min_{a \in \boldsymbol{H}} T_{a,i} - \ T_{c,i} - U \geq (-M)(1 - X_{c,i}) \ \forall \ c \in \boldsymbol{C} \quad (3)$$

Model description

This hospital selection model can help emergency medical technicians (EMTs) decide where to send patients when they arrive at the scene, and minimizes the time for a patient to receive definitive treatment. If the shortest time for a patient to receive definitive treatment is by sending them to an EVT-capable hospital, $X_{a,i}$ will equal 1 for some $a \in H$. Otherwise, the patient is sent to an rt-PA hospital first and $X_{a,i}$ will equal 1 for some $a \in C$. p_i is the probability that patient *i* has AIS without LVO, conditional on the number of the Cincinnati Prehospital Stroke Scale (CPSS) symptoms tested and found by the EMTs at the scene, and $1 - p_i$ is the probability that patient i has LVO.

Objective function (1) consists of two scenarios of expected time calculations. When a patient is sent to an EVT-capable hospital the expected time to receive definitive treatment is $S_i + T_{a,i} + \ Q_a \ + p_i \ D_a + (1 - p_i)\overline{D}_a$. The expected time to receive definitive treatment when a patient is first sent to an rt-PA hospital and who may then be transferred to an EVT-capable hospital is $S_i + T_{a,i} + Q_a + p_i D_a + (1 - p_i)(A + E_a)$. Transfer time E_a includes the driving time from the rt-PA hospital to the nearest EVT-capable hospital and the door-to-treatment duration in that EVT-capable hospital. Constraint (2) shows that a patient can only be sent to one hospital selected by the model. Constraint (3) dictates that when the time difference between the scene to an rt-PA hospital and from the scene to the nearest EVT-capable hospital is less than U seconds, the patient (with or without LVO) is sent directly to the EVT-capable hospital and not to the rt-PA.

Table S1. The number of patients sent to EVT-capable hospital as tolerable bypass transport threshold U and administration time A gradually decrease. (Proposed model. The probability measure is from Scheitz et al.[18])

$A \backslash U$ (min.)	15	14	13	12	11	10	9	8
46.5	7678	7678	7655	7628	7619	7595	7574	7563
45.5	7678	7678	7655	7626	7616	7590	7569	7551
44.5	7678	7678	7655	7626	7616	7590	7569	7549
43.5	7678	7678	7655	7625	7615	7585	7564	7544
42.5	7678	7678	7655	7625	7615	7585	7562	7539
41.5	7678	7677	7654	7622	7611	7580	7556	7533
40.5	7678	7677	7645	7608	7596	7565	7541	7516
39.5	7678	7677	7645	7608	7596	7561	7537	7511
38.5	7678	7677	7645	7607	7595	7555	7530	7502
37.5	7678	7677	7645	7607	7591	7550	7525	7494
36.5	7678	7677	7645	7607	7585	7540	7515	7483
35.5	7678	7677	7645	7605	7583	7535	7507	7475
34.5	7678	7677	7645	7604	7580	7528	7498	7466
33.5	7678	7677	7645	7603	7577	7520	7489	7456
32.5	7678	7677	7645	7603	7577	7516	7484	7447

31.5	7678	7677	7645	7602	7575	7509	7473	7431
30.5	7678	7677	7645	7602	7574	7497	7450	7402
29.5	7678	7677	7645	7602	7573	7486	7436	7380
28.5	7678	7677	7645	7602	7573	7480	7429	7366
27.5	7678	7677	7645	7602	7573	7472	7421	7354
26.5	7678	7677	7645	7602	7573	7464	7413	7341
25.5	7678	7677	7645	7602	7573	7462	7410	7336
24.5	7678	7677	7645	7602	7573	7457	7402	7327
23.5	7678	7677	7645	7602	7573	7455	7399	7323
22.5	7678	7677	7645	7602	7573	7450	7394	7316
21.5	7678	7677	7645	7602	7573	7448	7392	7313
20.5	7678	7677	7645	7602	7573	7446	7389	7310
19.5	7678	7677	7645	7602	7573	7446	7388	7309
18.5	7678	7677	7645	7602	7573	7444	7386	7306
17.5	7678	7677	7645	7602	7573	7439	7381	7301
16.5	7678	7677	7645	7602	7573	7434	7372	7290
15.5	7678	7677	7645	7602	7573	7434	7370	7287
14.5	7678	7677	7645	7602	7573	7434	7370	7286
13.5	7678	7677	7645	7602	7573	7432	7367	7282
12.5	7678	7677	7645	7602	7573	7431	7366	7281
11.5	7678	7677	7645	7602	7573	7430	7365	7280
10.5	7678	7677	7645	7602	7573	7430	7364	7278
9.5	7678	7677	7645	7602	7573	7430	7362	7276
8.5	7678	7677	7645	7602	7573	7430	7362	7276
7.5	7678	7677	7645	7602	7573	7430	7362	7276
6.5	7678	7677	7645	7602	7573	7430	7362	7274
5.5	7678	7677	7645	7602	7573	7430	7362	7274
4.5	7678	7677	7645	7602	7573	7430	7362	7274
3.5	7678	7677	7645	7602	7573	7430	7362	7274
2.5	7678	7677	7645	7602	7573	7430	7362	7274
1.5	7678	7677	7645	7602	7573	7430	7362	7274
0.5	7678	7677	7645	7602	7573	7430	7362	7274

$A\backslash U$ (min.)	7	6	5	4	3	2	1
46.5	7553	7543	7542	7542	7542	7542	7542
45.5	7540	7529	7527	7527	7527	7527	7527
44.5	7537	7524	7522	7521	7521	7521	7521
43.5	7525	7512	7510	7509	7509	7509	7509
42.5	7516	7501	7497	7496	7495	7495	7495
41.5	7509	7493	7487	7486	7484	7484	7484
40.5	7488	7468	7462	7461	7459	7458	7458
39.5	7480	7459	7453	7450	7448	7447	7447
38.5	7467	7440	7434	7430	7427	7426	7426
37.5	7459	7422	7416	7411	7408	7407	7407

36.5	7446	7408	7402	7397	7393	7392	7391
35.5	7436	7395	7389	7384	7378	7377	7376
34.5	7425	7384	7376	7371	7364	7362	7360
33.5	7414	7371	7363	7357	7349	7346	7344
32.5	7404	7360	7352	7346	7338	7333	7329
31.5	7387	7337	7328	7322	7313	7308	7300
30.5	7357	7300	7291	7285	7276	7270	7262
29.5	7335	7272	7260	7251	7241	7231	7221
28.5	7318	7252	7239	7229	7217	7205	7195
27.5	7305	7234	7219	7204	7190	7176	7154
26.5	7288	7213	7194	7177	7163	7149	7119
25.5	7278	7202	7179	7162	7147	7133	7098
24.5	7262	7184	7160	7142	7120	7103	7063
23.5	7251	7171	7145	7126	7103	7085	7045
22.5	7242	7130	7102	7082	7059	7038	6994
21.5	7238	7112	7083	7063	7039	7013	6960
20.5	7234	7100	7068	7048	7024	6995	6931
19.5	7231	7094	7060	7040	7016	6986	6920
18.5	7227	7089	7050	7026	6998	6965	6890
17.5	7222	7084	7043	7018	6990	6957	6878
16.5	7211	7070	7018	6980	6952	6917	6829
15.5	7208	7066	7013	6973	6943	6905	6813
14.5	7206	7059	7000	6958	6927	6889	6785
13.5	7199	7052	6986	6941	6903	6863	6747
12.5	7195	7048	6980	6931	6892	6845	6700
11.5	7193	7044	6975	6923	6876	6822	6664
10.5	7191	7037	6964	6907	6860	6805	6630
9.5	7188	7032	6959	6898	6848	6788	6597
8.5	7184	7028	6954	6892	6839	6774	6569
7.5	7184	7027	6950	6886	6828	6756	6531
6.5	7182	7025	6945	6879	6818	6742	6511
5.5	7182	7024	6943	6875	6808	6727	6489
4.5	7182	7024	6940	6867	6796	6711	6464
3.5	7179	7021	6936	6863	6792	6705	6444
2.5	7179	7021	6936	6858	6780	6685	6406
1.5	7179	7021	6935	6851	6771	6675	6382
0.5	7179	7021	6935	6845	6762	6661	6358

Data S2: An Alternative Probability Measure Conditional on the Number of CPSS Symptoms

Based on Richards et al.,[19] the probabilities that a patient has LVO conditional on three, two, and one of three CPSS symptoms are 0.727, 0.343, and 0.343, respectively. In our historical data, there were 7,678 patients who had a suspected stroke in Taipei City. Among these patients, 4,037 had three CPSS symptoms, 1,319 had two symptoms, and 2,322 had one symptom. If the probability measure was based on Richards et al.,[19] the numbers of patients extracted from those with three, two, and one CPSS symptoms were 2,935, 429, and 452, respectively, so 3,816 patients were assumed to have LVO, and the other 3,862 patients were assumed to be without LVO.

Table S2. The number of patients sent to EVT-capable hospital as tolerable bypass transport threshold U and administration time A gradually decrease. (Proposed model. The probability measure is from Richards et al.[19])

$A\backslash U$ (min.)	15	14	13	12	11	10	9	8
46.5	7678	7678	7678	7678	7678	7678	7678	7678
45.5	7678	7678	7678	7678	7678	7678	7678	7678
44.5	7678	7678	7678	7678	7678	7678	7678	7678
43.5	7678	7678	7678	7678	7678	7678	7678	7678
42.5	7678	7678	7678	7678	7678	7678	7678	7678
41.5	7678	7678	7678	7678	7678	7678	7678	7678
40.5	7678	7678	7678	7678	7678	7678	7678	7678
39.5	7678	7678	7678	7678	7678	7678	7678	7678
38.5	7678	7678	7678	7678	7678	7678	7678	7678
37.5	7678	7678	7678	7678	7678	7678	7678	7678
36.5	7678	7678	7678	7678	7677	7677	7677	7677

35.5	7678	7678	7678	7678	7677	7677	7677	7677
34.5	7678	7678	7666	7656	7654	7654	7654	7654
33.5	7678	7678	7657	7639	7637	7637	7637	7637
32.5	7678	7678	7656	7638	7636	7636	7636	7636
31.5	7678	7678	7656	7636	7633	7633	7633	7633
30.5	7678	7678	7656	7633	7626	7625	7625	7625
29.5	7678	7678	7656	7632	7625	7620	7618	7618
28.5	7678	7678	7655	7629	7621	7613	7610	7610
27.5	7678	7678	7655	7629	7621	7612	7604	7604
26.5	7678	7678	7655	7625	7617	7607	7595	7595
25.5	7678	7678	7655	7625	7616	7604	7587	7583
24.5	7678	7678	7655	7625	7615	7598	7580	7576
23.5	7678	7678	7655	7625	7615	7585	7562	7549
22.5	7678	7678	7655	7625	7615	7584	7561	7541
21.5	7678	7678	7655	7625	7615	7578	7554	7529
20.5	7678	7678	7655	7625	7615	7578	7554	7528
19.5	7678	7678	7655	7625	7615	7578	7554	7528
18.5	7678	7678	7655	7625	7615	7575	7551	7521
17.5	7678	7678	7655	7625	7615	7568	7544	7512
16.5	7678	7678	7655	7625	7615	7567	7543	7511
15.5	7678	7678	7655	7625	7615	7563	7539	7507
14.5	7678	7678	7655	7625	7615	7560	7536	7503
13.5	7678	7678	7655	7625	7615	7556	7532	7499
12.5	7678	7678	7655	7625	7615	7551	7524	7490
11.5	7678	7678	7655	7625	7615	7550	7521	7487
10.5	7678	7678	7655	7625	7615	7549	7519	7482
9.5	7678	7678	7655	7625	7615	7549	7519	7480
8.5	7678	7678	7655	7625	7615	7549	7518	7478
7.5	7678	7678	7655	7625	7615	7548	7515	7475
6.5	7678	7678	7655	7625	7615	7548	7515	7475
5.5	7678	7678	7655	7625	7615	7548	7513	7473
4.5	7678	7678	7655	7625	7615	7548	7512	7471
3.5	7678	7678	7655	7625	7615	7548	7512	7470
2.5	7678	7678	7655	7625	7615	7548	7512	7468
1.5	7678	7678	7655	7625	7615	7548	7512	7468
0.5	7678	7678	7655	7625	7615	7548	7512	7468

$A\backslash U$ (min.)	7	6	5	4	3	2	1
46.5	7678	7678	7678	7678	7678	7678	7678
45.5	7678	7678	7678	7678	7678	7678	7678
44.5	7678	7678	7678	7678	7678	7678	7678
43.5	7678	7678	7678	7678	7678	7678	7678
42.5	7678	7678	7678	7678	7678	7678	7678
41.5	7678	7678	7678	7678	7678	7678	7678

40.5	7678	7678	7678	7678	7678	7678	7678
39.5	7678	7678	7678	7678	7678	7678	7678
38.5	7678	7678	7678	7678	7678	7678	7678
37.5	7678	7678	7678	7678	7678	7678	7678
36.5	7677	7677	7677	7677	7677	7677	7677
35.5	7677	7677	7677	7677	7677	7677	7677
34.5	7654	7654	7654	7654	7654	7654	7654
33.5	7637	7637	7637	7637	7637	7637	7637
32.5	7636	7636	7636	7636	7636	7636	7636
31.5	7633	7633	7633	7633	7633	7633	7633
30.5	7625	7625	7625	7625	7625	7625	7625
29.5	7618	7618	7618	7618	7618	7618	7618
28.5	7610	7610	7610	7610	7610	7610	7610
27.5	7604	7604	7604	7604	7604	7604	7604
26.5	7593	7593	7593	7593	7593	7593	7593
25.5	7581	7581	7581	7581	7581	7581	7581
24.5	7573	7573	7573	7573	7573	7573	7573
23.5	7546	7543	7542	7542	7542	7542	7542
22.5	7538	7534	7533	7533	7533	7533	7533
21.5	7520	7512	7511	7511	7511	7511	7511
20.5	7513	7501	7496	7495	7495	7495	7495
19.5	7506	7492	7487	7485	7485	7485	7485
18.5	7494	7478	7472	7469	7469	7469	7469
17.5	7481	7439	7433	7430	7428	7428	7428
16.5	7470	7427	7421	7417	7413	7413	7413
15.5	7465	7418	7412	7408	7404	7403	7403
14.5	7461	7411	7405	7401	7396	7392	7392
13.5	7456	7401	7395	7391	7386	7382	7379
12.5	7447	7389	7383	7378	7372	7368	7365
11.5	7444	7383	7375	7370	7364	7359	7356
10.5	7439	7376	7365	7358	7351	7346	7342
9.5	7437	7374	7358	7350	7343	7338	7332
8.5	7433	7370	7353	7345	7337	7328	7317
7.5	7427	7362	7343	7333	7320	7308	7273
6.5	7427	7362	7342	7329	7312	7297	7256
5.5	7425	7357	7337	7322	7304	7287	7240
4.5	7423	7354	7331	7316	7293	7274	7221
3.5	7422	7353	7330	7314	7289	7268	7210
2.5	7420	7351	7325	7309	7283	7257	7192
1.5	7419	7349	7319	7301	7274	7243	7169
0.5	7412	7341	7309	7290	7263	7229	7145

Table S3. Sensitivity analysis for adjusting tolerable bypass transport threshold *U* and the administration time *A*. (The probability measure is based on Richards et al.[19])

Tolerable bypass transport threshold *U* (minutes)	Administration time *A* (minutes)	Number of patients sent to rt-PA hospitals first	Number of patients sent directly to EVT-capable hospitals	Expected time that patients receive definitive treatment (minutes)
15	46.5	0	7,678	117.12
7	23.5	132	7,546	117.08

rt-PA hospital: only provides intravenous thrombolysis.

Sensitivity results

Using the probability measure based on Richards et al.,[19] the initial parameter settings again result in no patients being sent to rt-PA hospitals because the 15-minute tolerable bypass transport threshold is met by all 7,678 patients. Therefore, we conduct a similar sensitivity analysis to determine the appropriate parameters for the model, again using the Richards et al.[19] probability measure. The full results of the model with different U and A are shown in Table S2. When U is 13 minutes, and A is 34.5 minutes, 12 patients are first sent to rt-PA hospitals and can tolerate the transfer. When U is 7 minutes, and A is 23.50 minutes, 132 patients are sent to rt-PA hospitals (see Figure S1). The total expected time reduction for 7,678 patients is 255.93 minutes more than the results of the model with its initial parameters. That is, the 132 non-LVO patients who are sent to rt-PA hospitals can receive definitive treatment an average of 1.93 minutes quicker (see Table S3).

Table S4. The mean time (in min.) for a patient to receive definitive treatment under the five strategies for deciding the receiving hospital. ($U = 15$, $A = 46.5$, and the probability measure is based on Richards et al.[19])

	Strategy a	Strategy b	Strategy c	Strategy d	Strategy e
Trial 1	140.20	139.58	117.03	138.97	139.20
Trial 2	140.30	139.52	117.13	138.98	139.13
Trial 3	140.35	139.88	117.08	139.20	139.47
Trial 4	140.60	139.73	117.10	139.17	139.37
Trial 5	140.17	139.47	117.12	138.97	139.12

Comparisons with other strategies for deciding the receiving hospitals

When applying the probability measure from Richards et al.,[19] strategy c still achieves the shortest time for a patient to receive definitive treatment (see Table S4). The average time difference between strategies c and b is 22.6 minutes, indicating that each patient can receive definitive treatment an average of 22.6 minutes quicker using strategy c. Patients are sent to all six EVT-capable hospitals under strategy b, but only to EVT-capable hospitals B2 and B3 under strategy c because of the differences in door-to-treatment time in hospitals (see Table S5).

Table S5. The number of patients sent to each receiving EVT-capable hospitals under different strategies and trials. ($U = 15$, $A = 46.5$, and the probability measure is based on Richards et al.[19])

	B1	B2	B3	B4	B5	B6
strategy b	983	2,104	836	1,234	1,397	1,124
strategy c	0	3,802	3,876	0	0	0

Table S6. The mean time (in min.) for a patient to receive the definitive treatment under the five trials. (The probability measure is from Richards et al.[19])

Tolerable bypass transport threshold U (minutes)	Administration time A (minutes)	Expected time for a patient to receive definitive treatment (minutes)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
15.00	46.50	117.12	117.03	117.13	117.08	117.10	117.12
7.00	23.50	117.08	117.03	117.13	117.07	117.10	117.10

Figure S1. Proportion of patients sent directly to an EVT-capable hospital at different values of U when is 46.5 and 23.5 minutes.

U (minute): the time difference between the scene to any rt-PA hospital and the scene to the nearest EVT-capable hospital. A (minute): the time interval from the first image of CT angiography of brain shown on the computer screen to an rt-PA hospital departure.

Figure S2. Geographic distribution of EVT-capable hospitals in the city.