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Network analysis of stroke systems of care in Korea

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ABSTRACT

Background The landscape of stroke care has shifted from stand-alone hospitals to cooperative networks among hospitals. Despite the importance of these networks, limited information exists on their characteristics and functional attributes.

Methods We extracted patient-level data on acute stroke care and hospital connectivity by integrating national stroke audit data with reimbursement claims data. We then used this information to transform interhospital transfers into a network framework, where hospitals were designated as nodes and transfers as edges. Using the Louvain algorithm, we grouped densely connected hospitals into distinct stroke care communities. The quality and characteristics in given stroke communities were analysed, and their distinct types were derived using network parameters. The clinical implications of this network model were also explored.

Results Over 6 months, 19 113 patients with acute ischaemic stroke initially presented to 1009 hospitals, with 3114 (16.3%) transferred to 246 stroke care hospitals. These connected hospitals formed 93 communities, with a median of 9 hospitals treating a median of 201 patients. Derived communities demonstrated a modularity of 0.904, indicating a strong community structure, highly centralised around one or two hubs. Three distinct types of structures were identified: single-hub (n=60), double-hub (n=22) and hubless systems (n=11). The endovascular treatment rate was highest in double-hub systems, followed by single-hub systems, and was almost zero in hubless systems. The hubless communities were characterised by lower patient volumes, fewer hospitals, no hub hospital and no stroke unit.

Conclusions This network analysis could quantify the national stroke care system and point out areas where the organisation and functionality of acute stroke care could be improved.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Stroke care has recently been evolving towards forming collaborative networks among hospitals, but efficiencies have not been evaluated.

WHAT THIS STUDY ADDS

⇒ A total of 1009 nationwide hospitals involved in acute stroke care were clustered into 93 functional network units, most of which were centralised linkages towards single or double hubs.

⇒ While single-hub and double-hub systems presented similar efficacies in patient transfers, endovascular treatment and mortalities, it could identify the hubless system that was vulnerable to the configuration of hospital networks and near-zero endovascular treatment performance.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This could be used to take an assessment and renovate local stroke systems in terms of the regional hospital organisations.

INTRODUCTION

Advancements in stroke treatment, such as endovascular treatment (EVT), have triggered changes in stroke care systems, expanding access to advanced treatments.[1] This shift has transformed stroke care from a single hospital model to networks of hospitals that work together to provide comprehensive acute stroke treatments.[2 3] These networks have been established through prehospital triage restructuring, interhospital transfer enhancement and the formation of regional stroke networks.[4 5]

While stroke networks have evolved in various forms over the past decade,[6–8] the diversity among them may result in uneven functioning.[9 10] Understanding the characteristics and functionality of stroke networks is essential to optimise those imbalanced situations by restructuring the delivery of acute stroke care.[11] In Korea, there are over a thousand hospitals where patients seek treatment for acute stroke. However, only a small fraction of these hospitals provide acute stroke care; even fewer are accredited stroke centres or offer EVT.[12 13] The Korean hospital system, historically, has not implemented an official tier system among hospitals, leading to significant regional disparities in accessing acute stroke treatments like intravenous thrombolysis (IVT), EVT, decompressive surgery and stroke unit (SU) care. This lack of a structured system often necessitates interhospital transfers, typically arranged through individual contacts rather than a formal network.[14] Recognising the need for more coordinated stroke care, the Korean government has recently initiated a pilot project. This project aims to establish predefined stroke networks, incentivising their use through preferential reimbursement policies.

To address this issue, our study applies contemporary network science techniques, offering a more comprehensive perspective than traditional analyses in epidemiology or clinical research.[15–17] These techniques acknowledge the interdependencies within the hospital network, allowing us to capture and understand the structure of interactions among hospitals. In our analysis, we have transformed these interactions into nodes (representing hospitals) and edges (representing interhospital transfers), consistent with the standard format in network science. Furthermore, we have grouped densely connected hospitals as a 'stroke community' using a popular community detection method. The quality and characteristics of these derived stroke communities were assessed using a variety of measures from network science. To comprehensively evaluate the impact of these stroke communities, we chose to focus on two critical response variables: EVT rates and 1 year mortality. This dual focus is particularly relevant in network analysis as it encapsulates both the effectiveness of clinical care (1 year mortality) and the diffusion of innovation within the network (EVT rates).

METHODS

Study subjects and data collection

This study used data from the Acute Stroke Quality Assessment Program (ASQAP), a national stroke audit programme administered by the Korea Health Insurance Review and Assessment Service (HIRA).[13] The ASQAP aims to evaluate the quality of acute stroke care provided by stroke care hospitals (SCHs) in Korea. All individuals admitted to SCHs through the emergency room within 7 days of stroke onset were included in the ASQAP. For this study, we analysed data from patients with acute ischaemic stroke (AIS) obtained from the seventh ASQAP assessment. To be eligible for the seventh assessment, SCHs were required to have treated 10 or more patients with acute stroke between 1 July and 31 December 2016.

Demographics, time intervals from onset to arrival, interhospital transfers, baseline stroke severity measured by National Institutes of Health Stroke Scale (NIHSS), administration of IVT, and functional outcome at discharge were obtained from the ASQAP database.[12] In addition, hospital size, number of neurologists and provision of SU care at SCHs were extracted from the ASQAP database. To gather information on hospital connections during the acute stage of stroke, administration of EVT and mortality, the ASQAP database was linked with reimbursement claims and death certificate data. Since South Korea has a single-payer system where the National Health Insurance Service and complementary medical aid programme cover the whole national population and reimbursement claims from any type of hospital,[18–20] this linkage provided us with comprehensive data. During the data collection process, interhospital transfers were defined as sequential hospitalisations of the same patient at two different facilities, with the discharge day of the sending hospital being the same or 1 day earlier than the admission date of the receiving hospital.[21] This enabled the identification of small-sized or medium-sized hospitals or clinics other than SCHs, which were operationally defined as adjacent facilities.

Study protocol approval and ethical statements

In compliance with the Act on the Protection of Personal Information, the HIRA provided patient and hospital data without any individual identifiers under the Joint Project on Quality Assessment Research, thus ensuring the study's compliance with all applicable privacy regulations.

Analysis

Establishing the interhospital connection database

The process involved compiling initial hospital visits and subsequent transfers, thereby classifying patient transitions into direct visits/stays, as well as sending and receiving actions. Patient transitions were then transformed into nodes (representing hospitals) and edges (representing interhospital transfers), which detailed both the direction and volume (weight) of these transfers.

Applying network analysis to identify stroke communities

Interhospital transfers, symbolised by the direction and weight of edges, allowed us to cluster densely linked hospitals heuristically. Our goal was to maximise the volume of interhospital transfers within a given cluster while minimising transfers between hospitals in different clusters. This was achieved using the Louvain algorithm,[22] which maximises the modularity of a partition. Modularity quantifies the difference in the density of internal links between a clustered network and a randomly connected network with the same clusters (ie, a modularity of 1 implies an upper limit, whereas 0 indicates no significant difference from a random network). The algorithm initially assigns each node (representing a hospital) to a separate cluster. In the first step, the algorithm finds the maximum modularity gain from reassigning each node to one of its neighbouring clusters and relocates it only if the gain is positive. It then merges all nodes in the same cluster into a single node and repeats the first step until there are no more changes in modularity.[23] A more detailed explanation of the methods employed is provided in online supplemental box 1.

Characterising the derived stroke communities

We used the modularity value Q to evaluate the overall quality of the derived stroke communities. In addition, to assess the quality and capacity of each community, we used three key density metrics[24] (global density (K), mean intracommunity density ($\bar{K}_{intra}$), and mean intercommunity density ($\bar{K}_{inter}$) (online supplemental table 1). K measures the overall connectivity in the network, calculated as the ratio of the actual number of connections (edges) to the maximum possible number. $\bar{K}_{intra}$ and $\bar{K}_{inter}$ assess the connectivity among nodes within individual communities and between different communities, respectively, both using a similar ratio-based approach. According to empirical studies, a higher $\bar{K}_{intra}$ compared with a K, and a lower $\bar{K}_{inter}$ compared with a K, indicate well-defined, high-quality communities. This means that the average connections within each community are more numerous than those between different communities, signifying distinct and well-integrated stroke care communities within the network.[25]

Stroke communities were characterized based on patient-level and hospital-level attributes and network metrics.[26] We evaluated the capacity of each stroke community using the number of direct visits/stays, inter-hospital transfers, recanalisation therapies, bed size and provision of SU care. Degree centrality, group degree centralization (GDC), and the abovementioned three density metrics were employed as network metrics.

Degree centrality is a measure used in network science to assess the importance of each node within a network. As the network has directed edges, we summed up the number of incoming links for each node. Then, we divided it by the number of possible connections within the belonging community. GDC measures the level of centralisation in each community. It first calculates the difference between each node's degree centrality and the theoretical maximum in the belonging community. It then divides these values by the theoretical maximum and sums them up. A value close to 1 indicates high centralisation and a value close to 0 indicates low centralisation. A more detailed explanation for calculating GDC is provided in online supplemental table 2.

Clinical interpretation of the network model

We classified the communities by visually inspecting a diagram that schematically represents the network topology. We visualised each community as a node-link diagram that places nodes with a higher degree of centrality in the centre. A node with a degree centrality higher than 0.5, 0.3 and the rest were heuristically designated as a hub, an auxiliary hub and a spoke, respectively. Subsequently, based on their topology and the number of hubs in the community, we categorised them as single-hub, double-hub and hubless communities.

We made comparisons among the abovementioned three community categories based on patient-level and hospital-level attributes, including transfer rates within and between communities. EVT rates and 1 year mortality were also compared as outcome variables. We obtained complete 1 year mortality data by linking with the death certificate data from the National Statistics Office of Korea and used this measure as a surrogate for functional outcomes.[27,28] Network analysis was conducted using SQL-based in-house programmes, while the statistical analysis was performed using SAS Enterprise Guide V.7.1 (SAS Institute, Cary, North Carolina, USA).

RESULTS

Over the 6-month study period, a total of 19 113 patients suffering from AIS were admitted to SCHs. The ASQAP evaluated the quality of acute stroke care delivered to these patients, which is analysed in this study. In the immediate days following stroke onset, patients primarily sought care at 1009 hospitals, which included 246 SCHs and 763 adjacent facilities. Among these, 1831 patients (9.6%) were transferred from adjacent facilities to SCHs, while 1283 (6.7%) were transferred from SCHs to other SCHs. Ultimately, 2900 patients (15.2%) were transferred to the EVT-capable SCHs, SCHs that performed at least one EVT procedure for patients with AIS during the 6-month study period.

The median (IQR) of patient admission volume per SCH was 33.5 (14–124) patients for the 6-month study period. The distribution was skewed to the right, with the highest 30 SCHs (12.2%) treating 30 or more patients per month, whereas the lowest 109 SCHs (44.3%) treated less than 4 patients per month (figure 1 and table 1).

In examining the sending and receiving tendencies of each SCH, we found that the median values of the receiving and sending proportions regarding AIS were 8.3% and 9.7%, respectively. This differentiation is vividly represented in the encoded stacked bar graph (figure 1), which illustrates the divergent roles of SCHs according to their patient volumes. High-volume centres demonstrated a greater likelihood of receiving patients from other hospitals, whereas low-volume centres were more likely to transfer patients to other hospitals. When we examined the relationships between patient volume and the receiving and sending proportions, we observed a Spearman correlation coefficient of 0.61 ($p<0.001$) for the receiving proportion and −0.70 ($p<0.001$) for the sending proportion.

The Louvain algorithm obtained 93 densely linked stroke communities, displaying modularity ($Q = 0.90$), indicative of a strong community structure. The use of weighted and directional edge information elevated the modularity from 0.35 (a value derived when the communities were clustered only considering the existence of hospital links, or in other words, using unweighted and unidirectional edge information) to 0.90. Moreover, the derived stroke communities satisfied the condition for high-quality clustering; $\bar{K}_{intra}$ (0.312) exceeded K $\left(0.004\right)$, and $\bar{K}_{inter}$ $\left(0.002\right)$ was less than K.

The 93 communities consisted of a median of nine hospitals, including two SCHs, and a median of 201 patients (mean±SD, 218±152) visited each community over a span of 6 months. Of these patients, 82.7% remained at their initial hospitals, 5.7% were transferred

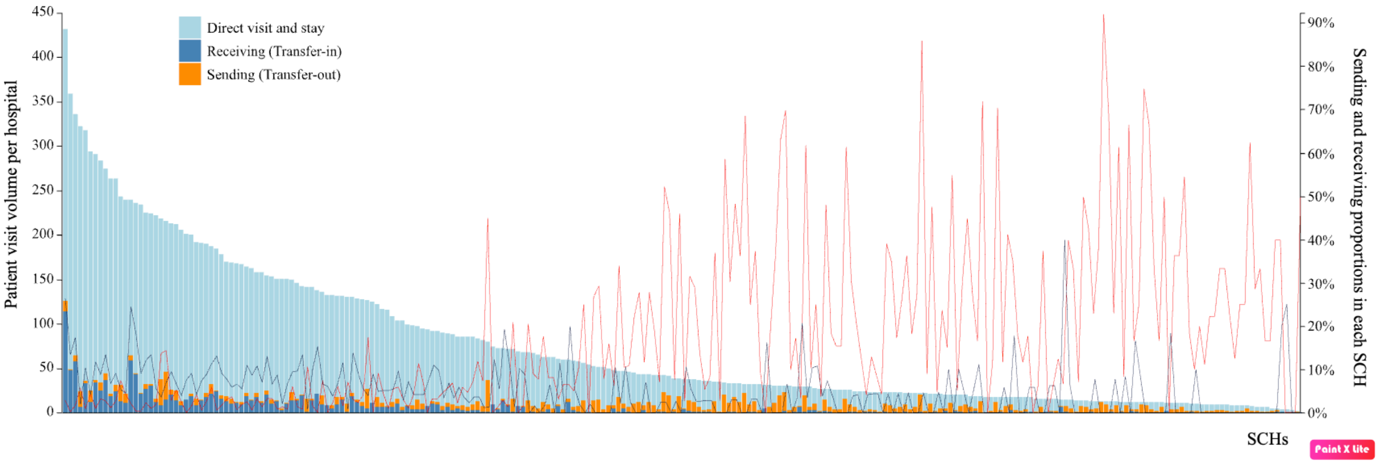

Figure 1 The distribution of AIS patient visit volume per hospital (y-axis on the left side) and the sending and receiving proportions (y-axis on the right side) in 246 SCHs. The stack bar graph represents the number of patients who were classified into direct-visit-and-stay (blue sky), sending (orange) and receiving (blue) in each SCH. The sending and receiving proportions in each SCH are overlaid on the red and blue lines, respectively. See the footnote of table 2 for the definition of patient visit volume. AIS, acute ischaemic stroke; SCH, stroke care hospital.

Table 1 Baseline characteristics of study subjects (n=19 113) and SCHs (n=246)

Variable	Values
Study subjects	
Age, years	69.2±12.9
Male	11 011 (57.6%)
Onset-to-arrival time, hours	9.4 (2.4–24.0)
EMS use	9966 (52.1%)
Baseline NIHSS Score	4 (1–8)
Smoking	4370 (22.9%)
Atrial fibrillation	3292 (17.2%)
IVT	2018 (10.6%)
EVT	1249 (6.5%)
SCHs	
Bed size	498 (336–769)
Number of neurologists	2 (1–5)
Presence of stroke unit	72 (29.3%)
Patient admission volume per hospital	33.5 (14.0–124.0)
Direct-visit-and-stay volume per hospital	31 (12–107.5)
Sending volume per hospital	4 (2–8)
Receiving volume per hospital	3 (1–16)
IVT per hospital	2 (0–13)
EVT per hospital	0 (0–7)

Values are presented as number (IQR), mean±SD or number (%).
Baseline NIHSS Score was missing in 206 patients (1.1%).
The figures presented here represent the cumulative estimates from the 6-month study period for the 246 SCHs participating in the ASQAP.

ASQAP, Acute Stroke Quality Assessment Program; EMS, emergency medical service; EVT, endovascular treatment; IVT, intravenous thrombolysis; NIHSS, National Institutes of Health Stroke Scale; SCH, stroke care hospital.

to hospitals within their community, 5.1% were transferred outside their own community and 5.2% were transferred from other communities (table 2). The median EVT rate per community was 5.9%, and the median 1 year mortality per community was 12.5%. There was a strong correlation between patient admission volume and other volumetric parameters, such as transfer volume, IVT volume and EVT volume (r>0.8, p<0.001, (online supplemental figure 1).

The use of geographical mapping afforded us unique insights into the size of the communities. It was observed that the longest diameter of the majority of these communities was typically less than 130 km in length. However, in approximately 14.0% of these communities, it extended beyond 200 km, with some reaching as far as 354.3 km (figure 2 and online supplemental figure 2).

The structure of most of these communities suggests the formation of highly centralised networks, often resembling a spindle shape. Such networks typically revolve around one or two major hospitals (hubs), which are interconnected with adjacent hospitals (spokes). Hubs received a median of 21 (IQR, 9–36) transfers, which corresponded to a median of 97.4% (IQR, 84.3%–100.0%) of total community transfers.

We measured the GDC to quantify the degree of centralisation within 93 individual communities. Results indicate a high degree of centralisation, as evidenced by a median GDC value of 0.99. This finding implies that patient transfers within most communities were heavily concentrated in a singular hub hospital.

Our study used schematic illustrations to elaborate on communities, revealing nodes and edges within each. The communities were arranged according to their GDC values, with an emphasis on their hub hospitals. This arrangement allows us to clearly depict the inherent network structures within these communities (figure 3). This diagram notably displayed close connections

Table 2 Characteristics of derived stroke communities (n=93)

Variables	Values
Patient visit volume	201 (109–288)
Number of hospitals	9 (5–14)
Number of SCHs	2 (1–3)
Presence of stroke unit	57 (61.3%)
Patient transition measures	
Direct-visit-and-stay, rate (%)	82.7 (78.2–87.3)
Intracommunity transfer, rate (%)	5.7 (3.9–9.1)
Transfer-in, rate (%)	5.1 (2.6–7.7)
Transfer-out, rate (%)	5.2 (3.5–8.0)
Network measures	
GDC	0.99 (0.71–1.00)
Intracommunity density	0.22 (0.13–0.40)
Intercommunity density	0.002 (0.001–0.003)
Recanalisation therapy and stroke outcome	
EVT	10.2 (4.2–19.8)
IVT	18.6 (9.0–28.8)
EVT rate (%)	5.9 (3.1–8.5)
One-year mortality (%)	12.5 (10.9–15.0)

Values are presented as the median (IQR), mean±SD or number (%).
Number of patients who visited any hospital belonging to each community at least once during the study period of 6 months
The denominator of these patient transition measures is patient visit volume defined above, and the numerator is the number of patients who visited and stayed at first hospitals (direct-visit-and-stay), who were transferred to other hospitals within communities (intracommunity transfer), who were transferred from outside communities (transfer-in), and transferred to outside communities (transfer-out).
Number of procedures performed during the study period of 6 months
The denominator of the EVT rate and 1 year mortality is the patient admission volume, defined as the number of patients who visited and stayed or were transferred to the corresponding hospitals.
EVT, endovascular treatment; GDC, group degree centralisation; IVT, intravenous thrombolysis; SCH, stroke care hospital.

centralised around one or two hub hospitals integral to the transportation system. The hubs and auxiliary hubs were defined as nodes with degree centrality >0.5 and >0.3, respectively (online supplemental figure 3).

According to the GDC values, the number of hubs and the discernible patterns, we classified the stroke communities into three distinct types: single-hub, double-hub and hubless systems (figure 3B and online supplemental figure 4). Age, baseline NIHSS Score, onset-to-arrival time and usage of emergency medical services (EMS) were found to be consistent across all three community types (table 3). The double-hub communities numerically had larger patient volumes, a greater number of hospitals and neurologists, and higher intracommunity transfer rates than the single-hub system. The EVT rate was highest in the double-hub system, followed by the single-hub system, and was almost zero in hubless systems. The 1 year mortality did not show any significant differences across these three types. The hubless systems, characterised by lower patient volume and fewer hospitals, did not feature a hub hospital. This absence of a hub hospital might result in no identifiable SUs, infrequent interhospital transfers and near-zero rates of EVT.

DISCUSSION

This study used contemporary network science techniques to illustrate the network structure of stroke care systems across Korea. We analysed 93 stroke communities, which were derived from 1009 hospitals involved in acute stroke care. These hospitals serve a nation of approximately 50 million inhabitants residing within an area of around 10 000 km^2.

Our analysis revealed that most of these stroke communities were highly centralised networks, primarily consisting of one-hub or two-hub hospitals. However, there were also a few communities that were poorly structured. Such inadequately formed communities might not be suitably equipped to provide advanced stroke treatment.

This study identified that 16.3% of patients were transferred from their first-visit hospitals to other medical facilities for acute stroke care. Over half of these interhospital transfers were from non-SCHs to SCHs, while the remaining transfers occurred between SCHs. These transfers were mostly necessitated by disparities in the transferring hospital's capacity to deliver higher levels of stroke care, deemed crucial in certain cases. Hospitals with a lower patient volume were more likely to refer patients to other facilities (figure 1).[29 30]

Interhospital transfer between SCHs may be unavoidable and sometimes essential. This is because it is not feasible for all SCHs to provide the highest levels of stroke care around the clock and throughout the year. However, transfers from non-SCHs to SCHs could be avoided. There is no reason to spend time in non-SCHs if transfers to SCHs are required. This situation could be improved through education to inform the importance of direct access to SCHs and the reorganisation of regional stroke systems to facilitate the direct dispatch of patients to SCHs via EMS. Enhancing such an intracommunity patient transportation process, with the support of EMS, could reduce intercommunity transfers, leading to a more efficient system.

Our study revealed that the median annual patient volume per SCH in Korea was 67 for AIS. This figure is lower than those reported in Japan (185 for AIS in 2015) and Denmark (330 for all types of strokes between 2003 and 2009). However, it is higher than that in Ontario, Canada, where the median annual patient volume per SCH was 28 for AIS between 2005 and 2012.[31–33] The distribution of volume of patients who had a stroke per SCH shows a right-skewness in both Korea and Canada, where over half of the hospitals provide acute stroke care to one or fewer patients per week.[33] Yet, it is essential to consider the gross geographical differences: Canada's land area is roughly 100 times larger than South Korea's.

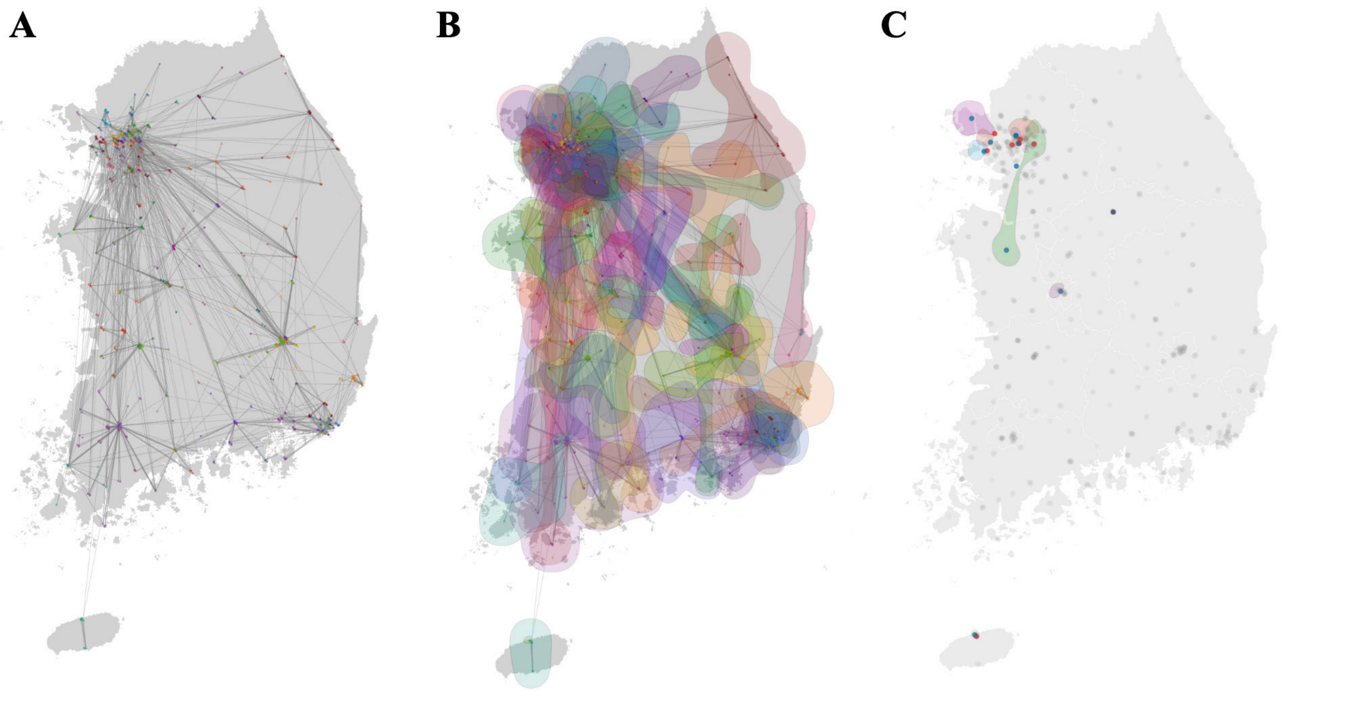

Figure 2 Geographical visualisation of stroke communities (A) with presumed boundaries (B) and 11 communities with a hubless system (C). The Louvain algorithm using weighted-and-directional connecting information partitioned 93 stroke communities represented by different coloured nodes (hospitals) with the thickness of edges (interhospital transfers and numbers) on the map (A). The boundaries of the communities visualised the extent of individual communities and overlapped territories among adjacent communities (B). In addition, 11 communities with hubless systems were depicted (C), which had no hub-and-spoke system (n=8), or only one hospital with no connection to other hospitals (n=3).

This vast geographical spread in Canada can present significant challenges in rapidly transferring patients with AIS to SCHs, contributing to the right-skewness of patient volume distribution. In contrast, South Korea's smaller geographical size, combined with adequate identification and planning, could facilitate more effective patient transfers. As a result, avoiding the skewness observed in the distribution of volume of patients who had a stroke might be possible.

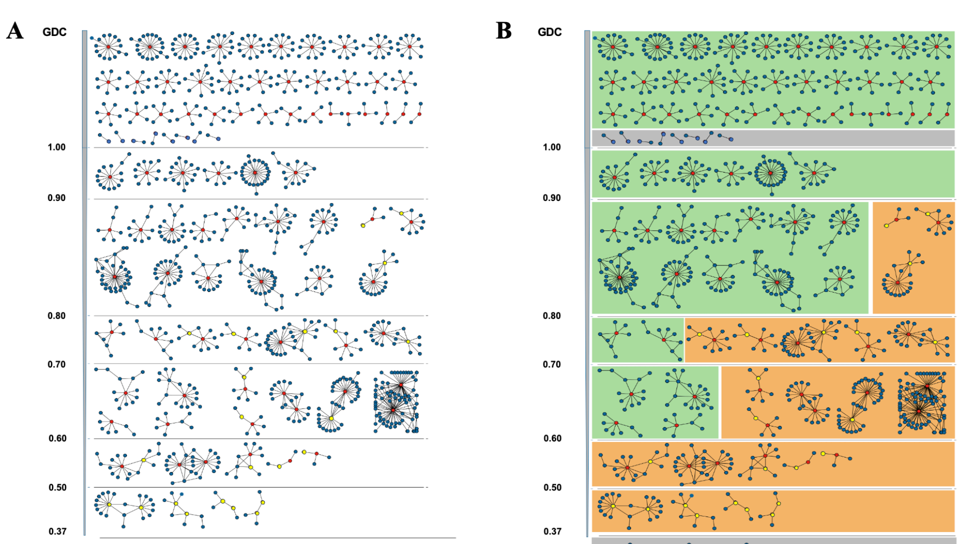

Figure 3 The network structure of stroke communities arrayed by group degree centralisation (A) and grouped by communities' characteristics (B). According to the number of connected nodes and degree centrality, individual nodes (hospital) were coloured: red >0.5 of degree centrality and yellow 0.3–0.5 with two or more edges, while others (blue, ≤0.3 of degree centrality or single edge). The configuration of communities was classified into single-hub (green), double-hub (orange) and hubless (grey) systems (B). GDC, group degree centralisation.

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Table 3 Comparisons between three categories of stroke communities according to their network structures

	Single-hub system (n=60)	Double-hub system (n=22)	Hubless system (n=11)	P value
Age, years	69.6±3.3	69.2±2.8	69.4±2.2	0.64
Male	129 (57.8%)	115 (58.1%)	70 (57%)	0.34
Onset to arrival time, hours	9.6 (7.7–11.2)	8.5 (7.3–10.3)	8.5 (5.8–9.4)	0.25
EMS use	117 (52.2%)	103 (52.4%)	67 (53.8%)	0.41
Patient admission volume	192 (122–272)	264 (141–335)	34 (18–61)	<0.001
Number of neurologists	7 (5–11)	11.5 (7–14)	2 (1–4)	<0.001
Number of hospitals	9 (6.5–14)	10.5 (7–20)	2 (1–2)	<0.001
Number of SCHs	2 (1–3)	3 (2–5)	1 (1–1)	<0.001
Number of stroke units	1 (0–1)	1 (0–2)	0 (0–0)	0.01
Intracommunity transfer rate (%)	5.7 (3.9–8.5)	7.7 (5.0–11.4)	1.5 (0.0–4.5)	0.01
Transfer-out rate (%)	4.9 (2.5–7.6)	6.7 (4.2–8.9)	4.0 (0.0–5.8)	0.06
Transfer-in rate (%)	6.1 (3.7–9.1)	4.4 (2.3–5.7)	4.0 (0.0–5.9)	0.01
EVT rate (%)	6.0 (3.5–8.7)	7.2 (4.6–8.1)	0.0 (0.0–2.7)	0.04
1 year mortality (%)	12.3 (10.9–14.4)	14.0 (11.0–14.9)	13.5 (5.6–24.6)	0.28

Values are presented as number (IQR), mean±SD or number (%).
The single-hub system denoted the communities where one hospital received most of the transfers within communities, that is, its degree centrality was >0.5, while the other hospitals had less than 0.3 of degree centrality. In the double-hub system, communities had one dominant hub (degree centrality >0.5), one auxiliary hub (degree centrality 0.3–0.5), or two complementary hubs (degree centrality 0.3–0.5). Lastly, the hubless system was a small-sized community (hospital number ≤2) or a single-hospital community without any dense links to other hospitals.
Values of p were estimated using the Kruskal–Wallis test and Fisher's exact test for overall group comparison, if appropriate.
Number of patients who visited and stayed or were transferred to any hospital belonging to each community during the study period of 6 months.
EMS, emergency medical services; EVT, endovascular treatment; SCH, stroke care hospital.

The Louvain algorithm employed in our study led to the identification of 93 communities, with a median of nine hospitals, including one or two hubs. These networks served as functional units providing acute stroke care in South Korea. The median GDC was 0.99, indicating that most derived communities were highly centralised. Moreover, the quality of the clusters estimated by the modularity (Q=0.90) would represent as notably high, indicating an overall high quality of clustering. The comparisons of the three density measures affirmed this high-quality clustering.

In our analysis, we observed a median intercommunity transfer rate of 5.7% (ranging from 3.9% to 9.1%), which might indicate either the incompleteness of stroke networks or potential overlaps between communities. This observation is particularly relevant given the constraints of the Louvain algorithm, which is designed to identify non-overlapping communities. This inherent limitation of the Louvain method highlights the need for more advanced community detection algorithms, such as Network Decomposition Overlapping Community Detection, to more accurately reflect the complex realities of healthcare networks.[34]

The hub hospitals were mostly equipped with SUs and capacitated to provide EVT. Among the three types of community structures, the single-hub and double-hub systems were largely comparable in many aspects. However, the hubless system drew our attention regarding lower patient volumes, no hub, no SU, lower transfer rates and a near-zero EVT rate. Accordingly, we could characterise the relatively low quality of stroke care in these hubless communities. Also, the urban location of these hubless communities underscores the importance of interhospital connectivity, surpassing the consideration of geographical proximity alone (figure 2C).

Each community in our study attended to approximately 200 patients with AIS over the 6-month study period. Comparatively, this patient volume per community is lower than that observed in a Comprehensive Stroke Center in the USA (~ 431 AIS).[35] Furthermore, nearly 40% of the communities in our study lacked SUs, and 48% reported an annual EVT case volume of fewer than 15. This figure is below the threshold case volume required to qualify as a Thrombectomy-Capable Stroke Center in the USA,[36] and inconsistent with the acknowledgement that a higher case volume correlates with improved quality of stroke care.[37 38] In addition, the variability in community size within South Korea is noteworthy. The longest diameter was less than 140 km in 86% of communities, extending over 200 km in 14% of communities. Smaller communities in close proximity to larger ones present an opportunity for reorganising the regional stroke systems in South Korea, thereby potentially enhancing the quality of acute stroke care.

In South Korea, the healthcare market is predominantly private and highly competitive, with minimal restrictions on accessing higher-level hospital services, even in emergency stroke care. This situation is unique compared with other countries in the Organization for Economic Co-operation and Development,[39 40] as evidenced by the lower usage of EMS in our study. This unrestricted access has led to over 1000 hospitals providing acute stroke care.[7 41] In response to this fragmented landscape, HIRA has recently introduced accreditation for stroke centres as part of the ASQAP. Additionally, the Ministry of Health and Welfare has begun a pilot project for stroke networks. Our study's findings could be instrumental in supporting and shaping these new initiatives.

The study has several limitations. First, the retrospective analysis of national audit data, an administrative data set, limits the comprehensiveness of the study data set. For example, the data set lacks detailed information regarding the rationale for interhospital transfers, time metrics relating to interhospital transfers and EVT, as well as the 3-month functional outcomes.

Second, we acknowledge a significant discrepancy in the number of ischaemic stroke cases in the ASQAP data set compared with the expected figures based on a recent statistical report from South Korea.[42] This variance could be partially attributed to the exclusion criteria of the ASQAP, which omits data from smaller hospitals (those with fewer than 10 patients during the 6-month study period) and cases not admitted through emergency departments. This exclusion potentially under-represents the total number of stroke cases. While leveraging the national claims data using International Classification of Diseases (ICD) codes could provide a broader scope of case identification, this approach has its drawbacks. Specifically, the accuracy of stroke case identification using ICD codes is not fully validated, and differentiating acute from chronic stroke events remains a challenge. Recent studies have indicated that only about 30% of cases are accurately classified as stroke when using ICD codes alone.[43]

Our third point of consideration is that this retrospective analysis limited our ability to detail patient dispositions among hospitals under specific clinical or regional conditions. Additionally, we didn't account for emerging connectivity aspects like telehealth, which are increasingly crucial in healthcare. Recognising these gaps, we suggest future research should employ advanced methods like the Exponential Random Graph Model to explore these dispositions and connectivity facets in-depth.[44] This approach would provide a more comprehensive understanding of healthcare networks and align with the evolving digital landscape in healthcare delivery.

Fourth, we acknowledge that the choice of 2016 as a study period, selected due to its proximity to the pivotal EVT trials of 2015,[45] and the ensuing reorganisation of regional stroke networks, may not fully capture the subsequent advancements in stroke care. Since then, it is likely that the infrastructure and implementation strategies for EVT in Korea, as in many other countries, have undergone significant evolution. This context should be considered when interpreting our findings. Future research may benefit from examining more recent data to provide insights into the current state of EVT utilisation and its outcomes. Lastly, the study subjects were limited to those admitted with a final diagnosis of ischaemic stroke. For more reliable network analysis, the next studies would warrant enrolling patients who were initially suspected of having a stroke.

In conclusion, our study results have significant practical implications for the organisation and delivery of acute stroke care. Our network analysis points out areas where the current geographical organisation and functionality of AIS care in Korea could be improved. Specific areas for improvement include addressing the right-skewness of patient volume per community, consolidating the smaller and more numerous communities, and rectifying the issues of hubless, small adjacent and excessively lengthy communities. These findings suggest that the regional stroke systems in Korea could be reorganised to optimise patient transportation to appropriate hospitals providing higher-level stroke care.

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REFERENCES

1 Adeoye O, Albright KC, Carr BG, *et al*. Geographic access to acute stroke care in the United States. *Stroke* 2014;45:3019–24.
2 Eng MS, Patel AV, Libman RB, *et al*. Improving regional stroke systems of care. *Curr Atheroscler Rep* 2017;19:52.
3 Higashida R, Alberts MJ, Alexander DN, *et al*. Interactions within stroke systems of care. *Stroke* 2013;44:2961–84.
4 Venema E, Groot AE, Lingsma HF, *et al*. Effect of Interhospital transfer on endovascular treatment for acute ischemic stroke. *Stroke* 2019;50:923–30.
5 Wu TY, Coleman E, Wright SL, *et al*. Helsinki stroke model is transferrable with 'real-world resources and reduced stroke thrombolysis delay to 34 min in Christchurch. *Front Neurol* 2018;9:290.
6 Mohamad NF, Hastrup S, Rasmussen M, *et al*. Bypassing primary stroke centre reduces delay and improves outcomes for patients with large vessel occlusion. *Eur Stroke J* 2016;1:85–92.
7 Brown AT, Wei F, Culp WC, *et al*. Emergency transport of stroke suspects in a rural state: opportunities for improvement. *Am J Emerg Med* 2016;34:1640–4.
8 Raychev RI, Stradling D, Patel N, *et al*. Evolution of a US County system for acute comprehensive stroke care. *Stroke* 2018;49:1217–22.
9 Pérez de la Ossa N, Abilleira S, Dorado L, *et al*. Access to endovascular treatment in remote areas. *Stroke* 2016;47:1381–4.
10 Levy M, Chen Y, Clarke R, *et al*. Socioeconomic differences in health-care use and outcomes for stroke and ischaemic heart disease in China during 2009–16: a prospective cohort study of 0·5 million adults. *Lancet Glob Health* 2020;8:e591–602.
11 Zachrison KS, Dhand A, Schwamm LH, *et al*. A network approach to stroke systems of care. *Circ Cardiovasc Qual Outcomes* 2019;12:e005526.
12 Kim JY, Lee KJ, Kang J, *et al*. Acute stroke care in Korea in 2013–2014: national averages and disparities. *J Korean Med Sci* 2020;35:e167.
13 Park H-K, Kim S-E, Cho Y-J, *et al*. Quality of acute stroke care in Korea (2008–2014): retrospective analysis of the nationwide and nonselective data for quality of acute stroke care. *Eur Stroke J* 2019;4:337–46.
14 Chung I, Bae H-J, Kim BJ, *et al*. Interactive direct Interhospital transfer network system for acute stroke in South Korea. *J Clin Neurol* 2023;19:125–30.
15 Miasnikof P, Shestopaloff AY, Bonner AJ, *et al*. A statistical density-based analysis of graph clustering algorithm performance. *J Complex Netw* 2020;8.
16 Wasserman S, Faust K. *Social Network Analysis*. Cambridge University Press, Available: https://www.cambridge.org/core/product/identifier/9780511815478/type/book
17 Blondel VD, Guillaume J-L, Lambiotte R, *et al*. Fast unfolding of communities in large networks. *J Stat Mech* 2008;2008:10008.
18 Song YJ. The South Korean health care system. *JMAJ* 2009;52:206–9.
19 Sohn M, Jung M. Effects of public and private health insurance on medical service utilization in the national health insurance system: national panel study in the Republic of Korea. *BMC Health Serv Res* 2016;16:503.
20 Lee T-J, Cheong C. Has the copayment ceiling improved financial protection in the Korean national health insurance system? evidence from the 2009 policy change. *J Prev Med Public Health* 2017;50:393–400.
21 Iwashyna TJ, Kahn JM, Hayward RA, *et al*. Interhospital transfers among medicare beneficiaries admitted for acute myocardial infarction at nonrevascularization hospitals. *Circ Cardiovasc Qual Outcomes* 2010;3:468–75.
22 Dugué N, Perez A. Directed Louvain: maximizing modularity in directed networks. *HAL* 2015.
23 Newman MEJ. Modularity and community structure in networks. *Proc Natl Acad Sci U S A* 2006;103:8577–82.
24 van LT, Marchiori E. Axioms for graph clustering quality functions. *Arxiv* 2013.
25 Miasnikof P, Shestopaloff AY, Bonner AJ, *et al*. A density-based statistical analysis of graph clustering algorithm performance. *J Complex Netw* 2020;8.
26 Faust K. Centrality in affiliation networks. *Social Networks* 1997;19:157–91.
27 Ganesh A, Luengo-Fernandez R, Wharton RM, *et al*. Time course of evolution of disability and cause-specific mortality after ischemic stroke: implications for trial design. *J Am Heart Assoc* 2017;6:e005788.
28 Eriksson M, Norrving B, Terént A, *et al*. Functional outcome 3 months after stroke predicts long-term survival. *Cerebrovasc Dis* 2008;25:423–9.
29 Lee KB, Park H-K, Park T-H, *et al*. Current status and problems of stroke units in Korea: results of a nationwide acute care hospital survey by the Korean stroke society. *J Korean Neurol Assoc* 2015;33:141–55.
30 Choi H-Y, Cha M-J, Nam HS, *et al*. Stroke units and stroke care services in Korea. *Int J Stroke* 2012;7:336–40.
31 Kada A, Ogasawara K, Kitazono T, *et al*. National trends in outcomes of ischemic stroke and prognostic influence of stroke center capability in Japan, 2010–2016. *Int J Stroke* 2019.
32 Svendsen ML, Ehlers LH, Ingeman A, *et al*. Higher stroke unit volume associated with improved quality of early stroke care and reduced length of stay. *Stroke* 2012;43:3041–5.
33 Hall RE, Fang J, Hodwitz K, *et al*. Does the volume of ischemic stroke admissions relate to clinical outcomes in the Ontario stroke system&quest. *Circ Cardiovasc Qual Outcomes* 2015;8:S141–7.
34 Ding Z, Zhang X, Sun D, *et al*. Overlapping community detection based on network decomposition. *Sci Rep* 2016;6:24115.
35 Man S, Zhao X, Uchino K, *et al*. Comparison of acute ischemic stroke care and outcomes between comprehensive stroke centers and primary stroke centers in the United States. *Circ Cardiovasc Qual Outcomes* 2018;11:e004512.
36 Commission TJ. Certification for Thrombectomy-capable stroke centers. n.d. Available: https://www.jointcommission.org/certification/certification_for_thrombectomycapable_stroke_centers.aspx
37 Lee K-J, Kim JY, Kang J, *et al*. Hospital volume and mortality in acute ischemic stroke patients: effect of adjustment for stroke severity. *J Stroke Cerebrovasc Dis* 2020;29:104753.
38 Stein LK, Mocco J, Fifi J, *et al*. Correlations between physician and hospital stroke thrombectomy volumes and outcomes. *Stroke* 2021;52:2858–65.
39 Song D, Tanaka E, Lee K, *et al*. Factors associated with early hospital arrival in patients with acute ischemic stroke. *J Stroke* 2015;17:159–67.
40 Mochari-Greenberger H, Xian Y, Hellkamp AS, *et al*. Racial/ethnic and sex differences in emergency medical services transport among hospitalized US stroke patients: analysis of the national get with the guidelines–stroke registry. *JAHA* 2015;4.
41 Mikulík R, Bunt L, Hrdlicka D, *et al*. Calling 911 in response to stroke: a nationwide study assessing definitive individual behavior. *Stroke* 2008;39:1844–9.
42 Kim JY, Kang K, Kang J, *et al*. Executive summary of stroke statistics in Korea 2018: A report from the epidemiology research council of the Korean stroke society. *J Stroke* 2019;21:42–59.
43 Kim JY, Lee K-J, Kang J, *et al*. Development of stroke identification algorithm for claims data using the multicenter stroke registry database. *PLoS One* 2020;15:e0228997.
44 Jiao C, Wang T, Liu J, *et al*. Using exponential random graph models to analyze the character of peer relationship networks and their effects on the subjective well-being of adolescents. *Front Psychol* 2017;8:583.

45 Smith EE, Saver JL, Cox M, *et al*. Increase in endovascular therapy in get with the guidelines-stroke after the publication of pivotal trials. *Circulation* 2017;136:2303–10.