Journal of Perinatology
https://doi.org/10.1038/s41372-021-01091-w

ARTICLE

Quantifying the variation in neonatal transport referral patterns using network analysis

Sarah N. Kunz[1,2] · Daniel Helkey[3,4] · Marinka Zitnik[5] · Ciaran S. Phibbs[3,6] · Joseph Rigdon[7] · John A. F. Zupancic[1,2] · Jochen Profit[3,4]

Received: 4 December 2020 / Revised: 31 March 2021 / Accepted: 30 April 2021

Abstract

Objective Regionalized care reduces neonatal morbidity and mortality. This study evaluated the association of patient characteristics with quantitative differences in neonatal transport networks.

Study design We retrospectively analyzed prospectively collected data for infants <28 days of age acutely transported within California from 2008 to 2012. We generated graphs representing bidirectional transfers between hospitals, stratified by patient attribute, and compared standard network analysis metrics.

Result We analyzed 34,708 acute transfers, representing 1594 unique transfer routes between 271 hospitals. Density, centralization, efficiency, and modularity differed significantly among networks drawn based on different infant attributes. Compared to term infants and to those transported for medical reasons, network metrics identify greater degrees of regionalization for preterm and surgical patients (more centralized and less dense, respectively [$p < 0.001$]).

Conclusion Neonatal interhospital transport networks differ by patient attributes as reflected by differences in network metrics, suggesting that regionalization should be considered in the context of a multidimensional system.

Introduction

Neonatal regionalization, which emphasizes matching patient needs with hospital care capabilities, has been widely recognized as a strategy to reduce neonatal morbidity and mortality [1–7]. Successfully regionalized perinatal care systems ensure that the need for neonatal care at a high-level neonatal intensive care unit (NICU) is recognized in a timely manner. Such needs are typically best met by antenatal transport of pregnant women to delivery centers as close as possible to a NICU that can provide the necessary care for the baby [8–14]. When antenatal transport is not possible, or when an infant's need for a higher level of care is discovered only after delivery, neonatal transport becomes necessary.

The flow of patients through neonatal transport networks is an important process to understand, because need for interhospital newborn transport has been linked to increased morbidity and mortality [5, 15–21]. Many care networks have assumed the same ideal referral patterns for all patients, based simply on illness acuity, geography, and hospital relationships. However, increasing specialization within neonatal care has resulted in NICUs with different areas of expertise and capabilities, including programs for specific congenital anomalies such as esophageal atresia,

These authors contributed equally: John A. F. Zupancic, Jochen Profit

✉ Sarah N. Kunz
skunz@bidmc.harvard.edu

1 Division of Newborn Medicine, Department of Pediatrics, Harvard Medical School, Boston, MA, USA

2 Department of Neonatology, Beth Israel Deaconess Medical Center, Boston, MA, USA

3 Division of Neonatal and Developmental Medicine, Department of Pediatrics, Stanford University School of Medicine, Palo Alto, CA, USA

4 California Perinatal Quality Care Collaborative, Palo Alto, CA, USA

5 Department of Biomedical Informatics, Harvard University, Boston, MA, USA

6 Health Economics Resource Center, Veterans Affairs Palo Alto Healthcare System, Menlo Park, CA, USA

7 Department of Biostatistics and Data Science, Wake Forest School of Medicine, Winston-Salem, NC, USA

Published online: 25 May 2021

congenital heart disease, or short bowel syndrome. Thus, structuring neonatal networks likely requires going beyond a "one size fits all" approach. In addition, just as selecting an infant's destination may need to account for specific medical and surgical conditions, other nonmedical factors (such as insurance status, socioeconomic context, and existing provider/hospital relationships) may contribute to how patients move through a referral network. However, previous analyses of factors influencing, and outcomes of, neonatal regionalization have been limited by study designs, such as before–after and interrupted time series designs, which are prone to bias. For this reason, network analysis, which approaches neonatal transport quantitatively and without a priori assumptions about hospital capabilities, may serve to improve our understanding of this field.

We have previously applied techniques from the field of network analysis to demonstrate how geography and certain patient attributes influence neonatal referral patterns [22]. Factors associated with infants being transported outside of the originating referral subnetwork included medical indications (e.g., major congenital anomalies and need for surgery) as well as nonmedical factors (e.g., insurance as the reason for transfer). A better understanding of how referral patterns are influenced by patient attributes is necessary, a task undertaken here with the application of network analysis to neonatal transports in a single state.

Materials/subjects and methods

This was a retrospective database study including all neonatal transfers <28 days conducted by California Perinatal Quality Care Collaborative (CPQCC) member hospitals that occurred between January 1, 2008 and December 31, 2012, the most recent years for which the full complement of data are available. As described previously, infants were included in this study using any of the following inclusion criteria: (i) birth weight 401–1500 g, (ii) gestational age 22 0/7 weeks to 29 6/7 weeks, or (iii) for infants >1500 g, either death, surgery, intubation, or positive pressure support for more than 4 h, readmitted for total bilirubin ≥25 and/or exchange transfusion, early bacterial sepsis, or acute transfer. We applied the following definitions to categorize transports: acute transfer was defined as transfer of an infant who required acute resolution of medical problems and who was transferred in order to obtain care that was not provided, or that could not be effectively provided, at the referring institution (e.g., staffing/census issues, insurance). Within CPQCC, the California Perinatal Transport System (CPeTS) is a system of more than 100 specialized NICUs that participate in the transport of infants in California and collects data on acute neonatal transports [22]. The CPQCC and CPeTS data were then linked to data from the Office of Statewide Health Planning and Development (OSHPD) Vital Statistics-Patient Discharge Data, which include financial, operational, and patient-level variables, compiled annually for every hospital in California. This data set links birth certificates with infant death certificates, as well as infant and maternal hospital discharge records, including all infant transfers and readmissions. Transfer type (surgical, medical, and insurance/other) was identified using CPQCC and CPeTS records. Non-acute transports, and those originating from or traveling to hospitals not included in the CPQCC network, from outside the state of California, or from outside the United States, and infants admitted from home, were excluded from the study.

We used network analysis methods to construct graphs representing the structure and direction of acute transport of infants through hospitals in California. Network graphs are composed of nodes and edges and can be used to mathematically represent the structure and strength of relationships between entities. In these graphs, nodes represent hospitals, and connections (also known as edges) between nodes record the total number and directionality of acute neonatal transports between each pair of hospitals. In this way, the network is both "directed" (that is, the direction of the transfer is retained) and "weighted" (that is, the number of transports between two hospitals is reflected). Separate graphs were constructed for each infant attribute of interest: (i) all transfers; (ii) birth weight (<750, 750–1500, 1501–2500, >2500 g); (iii) gestational age (<28, 28–31—6/7, 32–35—6/7, 36+ weeks); (iv) days of life at transport (<3, 3–7, 8–14, 15+ days); and (v) transfer type (surgical or medical reason for transfer). Transfer type was identified using CPQCC and CPeTS records, with ICD-9 codes indicating surgical evaluation or management used to identify surgical transfers in transfers of infants with reason not recorded. Graphs were constructed using all available data for each patient characteristic.

The graphs were characterized according to a predefined set of standard network metrics measuring different aspects of network structure and flow of patients. Simple descriptive metrics included the number of nodes (hospitals) and edges (unique transport paths), number of transports per infant, degree (number of incoming, outgoing, and total transports for each hospital), and percentage of transports to a regional hospital. Measures of network structure included the following: (i) centralization (the extent to which the network is dominated by individual nodes, measured by average Katz centrality of hospitals with incoming acute transfers) [23–25], which gives information on the extent to which the network is organized in a "hub-and-spoke" pattern around important hospitals; (ii) weighed density (the observed fraction of possible network connections, weighted by the maximum proportion of infants transferred through a single connection) [26], which gives information on the proportion of all possible transfer routes between hospitals that were actually used; (iii) efficiency (average shortest path length between nodes, measured by average global efficiency) [27–29], which is a measure of the shortest (non-geographical) path between two hospitals based on existing transfer routes; and (iv) modularity (the tendency of network connections to cluster into communities, applying the Walktrap method for community detection) [30–33], which measures the tendency of the network to break down into discrete communities of hospitals based on transfers between them. Of note, physical distance between hospitals does not impact these network metrics and was not considered in the analysis. Metrics for density, efficiency, centralization, and modularity were constructed to be comparable between networks of different sizes. The full, directed, weighted network was used to calculate all network metrics with the exception of efficiency, which was computed using an undirected unweighted representation of each network; this ensures metric values are between 0 and 1, a property common to all other selected metrics. We additionally calculated weighted network efficiency using directed weighted networks as a sensitivity analysis, and observed the same qualitative trends as the average global efficiency for all network types (available on request). Hospitals were categorized based on designations from the California Children's Services (CCS) levels of care [34, 35]. CCS designations include, in order of increasing care capabilities, Intermediate, Community, and Regional centers.

We used the network metrics to compare the different networks within each attribute to each other, using a permutation test as the method of comparison and using $p < 0.05$ as the threshold for statistical significance. Permutation tests were further used to identify significant pairwise differences while applying the Bonferroni correction as appropriate [36–38]. Standard errors were estimated using the statistical bootstrap, in which transfers were sampled with replacement, to estimate variation in the metrics, using 1000 bootstrap iterations [39]. Network visualization and statistical analyses were undertaken with Python using the NetworkX and Igraph packages [40, 41]. The study was approved by the institutional review boards of the investigators.

Results

We analyzed a data set of 2,576,104 hospital discharge records of 2,530,026 infants in California between 2008 and 2012. Disposition at the first encounter included discharge home (2,479,966), acute transfer to another hospital (34,657), transfer for other reasons including capacity planning or insurance (8623), or death (6780). At the transfer level, a total of 34,708 acute transfers of 33,691 infants were included in the analysis, representing 1594 unique transfer routes between 271 hospitals in California. Fifty-one infants had a subsequent acute transfer after their initial transfer, and some infants were transferred multiple times. Thirteen percent of transports involved very-low birth weight (VLBW; <1500 g) infants, and 7% of transports were for infants <28 weeks gestation. Patient characteristics are shown in Table 1.

Graphs of medical and surgical transfer networks are shown in Fig. 1. Additional networks stratified by each attribute (birth weight, gestational age, days of life at transport) are available in the Appendix (Supplementary Fig. 1). In all graphs, node size is proportional to the total number of infants transported into the hospital, node color denotes CCS level of care, and edge color indicates CCS level of the destination hospital. Relative to medical transports, the surgical transport network was more centralized, and almost all transports were to regional hospitals. In the less centralized medical transport network, several intermediate hospitals can be identified as "hubs." A summary of the network characteristics is shown in Table 2, with a summary by hospital CCS level of care provided in the Appendix (Supplementary Table 1).

Centralization, density, efficiency, and modularity differed significantly among networks drawn on different infant attributes (Table 3 and Fig. 2). Metrics each differ in scale, but have been chosen to be comparable between networks of different sizes. Density in neonatal transport networks is a measure of the average weight of transfer routes between hospitals, with larger values indicating more infants transferred through fewer major transfer routes. Larger values of efficiency and centralization correspond to a tendency toward a "hub-and-spoke" architecture, with many hospitals transferring patients into a few select centers [42]. Modularity corresponds to the degree to which transfers between hospitals are organized into smaller communities, typically structured around a high-level referral center, with highly modular networks easily partitioning into discrete smaller communities.

The transport networks for the smallest (<750 g) and lowest gestational age (<28 weeks) infants were more centralized and had lower density and efficiency, when compared to the largest (>2500 g) and highest gestational age (>36 weeks) infants, respectively ($p < 0.001$). Surgical transports also had higher centralization and lower density, with no difference in efficiency, when compared to medical transports.

The underlying community structure among the networks also differed significantly based on patient attribute. Medical transfers had significantly higher modularity ($p < 0.001$) compared with surgical transfers. Modularity also different significantly between networks defined by infant days of life at transfer. Modularity was highest for infants transferred <3 days of life, and declined significantly for the networks of infants transferred later in life ($p < 0.001$).

Table 1 Characteristics of infants included in the study.

	Infants transfered	Reason for transfer			Total transfers[a]
		Medical	Surgical	Insurance/other	
	N (%)	*N* (%)	*N* (%)	*N* (%)	*N* (%)
Total	*N* = 33,691	*N* = 20,302	*N* = 7394	*N* = 7012	*N* = 34,708
Sex					
Female	14,315 (42)	8627 (42)	3150 (43)	2956 (42)	14,733 (42)
Male	19,376 (58)	11,675 (58)	4244 (57)	4056 (58)	19,975 (58)
Birth weight					
<750 g	1120 (3)	740 (4)	394 (5)	30 (0)	1164 (3)
750–1500 g	3218 (10)	2465 (12)	746 (10)	125 (2)	3336 (10)
1500–2500 g	8664 (26)	5703 (28)	1417 (19)	1749 (25)	8869 (26)
≥2500 g	20,689 (61)	11,394 (56)	4837 (65)	5108 (73)	21,339 (61)
Gestational age					
<28 wks	2401 (7)	1660 (8)	747 (10)	91 (1)	2498 (7)
28–32 wks	2683 (8)	2121 (10)	452 (6)	177 (3)	2750 (8)
32–37 wks	10,231 (30)	6865 (34)	1548 (21)	2017 (29)	10,430 (30)
≥37 wks	18,376 (55)	9656 (48)	4647 (63)	4727 (67)	19,030 (55)
Days of life at transfer[b]					
<3 days	28,973 (86)	18,194 (90)	5034 (68)	6090 (87)	29,318 (84)
3–7 days	3031 (9)	1339 (7)	1022 (14)	701 (10)	3062 (9)
8–14 days	1234 (4)	435 (2)	682 (9)	135 (2)	1252 (4)
15+ days	1055 (3)	334 (2)	656 (9)	86 (1)	1076 (3)
Race/ethnicity[c]					
Non-Hispanic White	8157 (24)	6347 (31)	1956 (26)	157 (2)	8460 (24)
Non-Hispanic Black	1875 (6)	1400 (7)	504 (7)	46 (1)	1950 (6)
Hispanic	13,340 (40)	10,111 (50)	3502 (47)	185 (3)	13,798 (40)
Asian/NHOPI[d]	1942 (6)	1363 (7)	624 (8)	30 (0)	2017 (6)
Other	891 (3)	700 (3)	208 (3)	16 (0)	924 (3)

[a]Total number of transfers differs from total number of infants as some infants underwent >1 transfer.

[b]Infants transferred multiple times may be counted in >1 group based on days of life at each transfer.

[c]Race/ethnicity data missing for 7486 infants (7559 transfers).

[d]Native Hawaiian/other Pacific Islander.

Discussion

In this analysis, we have demonstrated that the shape and characteristics of neonatal interhospital transport networks differ by gestational age, birth weight, infant age, and transfer type. The analysis builds on previous work establishing the utility of using network analytic techniques to approach neonatal transport and regionalization [22]. Employing quantitative methodologies for studying neonatal regionalization can facilitate a richer and more complete understanding of the factors that shape transport networks, avoiding many of the biases of previous work relying on less quantitative measures. This foundational work will support a more rigorous approach to linking neonatal regionalization with patient outcomes and, ultimately, improving these care delivery systems.

Ideally, when the need for neonatal intensive care can be anticipated, maternal transport can be arranged prior to delivery. However, when neonatal transport must occur after delivery, the choice of destination hospital is typically based on the infant's illness acuity and type, as well as established referral relationships between hospitals, as is often observed empirically in clinical practice. Financial incentives may also drive delivery at outlying hospitals, accounting for a portion of postnatal transports to higher-level centers.

Birth weight and gestational age

The results of our analysis suggest that transports for the sickest infants are, indeed, concentrated into high-acuity centers, empirically validating the ability of network analysis

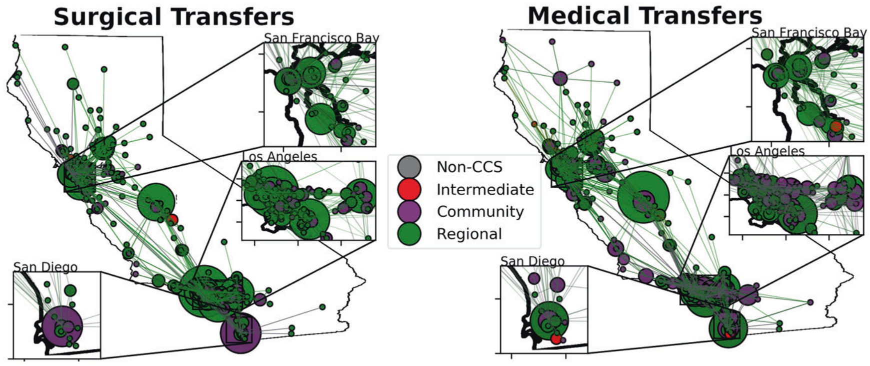

Fig. 1 Representative graphs of the networks defined by medical and surgical transfers. Circular nodes represent hospitals, with edges between nodes representing acute transports. Node size is proportional to the total number of infants transported into the hospital. Node color denotes California Children's Services (CCS) level of care, and edge color indicates CCS level of the destination hospital.

Table 2 Characteristics of the full network and networks defined by infant attributes.

	Nodes[a]	Edges[b]	Transfers[c]	Average in-degree[d]	Average out-degree[d]	Destination[e]		
						Intermediate	Community	Regional
						N (%)	*N* (%)	*N* (%)
Full network	271	1594	34,708	259.01	128.07	233 (0.7)	8186 (23.6)	25,714 (74.1)
Birth weight								
<750 g	210	304	1164	18.77	6.22	0 (0.0)	244 (21.0)	912 (78.4)
750–1500 g	252	559	3336	35.12	13.51	9 (0.3)	879 (26.3)	2395 (71.8)
1500–2500 g	265	872	8869	75.16	33.47	88 (1.0)	2298 (25.9)	6301 (71.0)
≥2500 g	267	1326	21,339	169.36	79.92	136 (0.6)	4765 (22.3)	16,106 (75.5)
Gestational age								
<28 wks	243	453	2498	30.84	10.72	0 (0.0)	596 (23.9)	1878 (75.2)
28–32 wks	253	543	2750	27.23	11.09	18 (0.7)	758 (27.6)	1917 (69.7)
32–37 wks	266	906	10,430	84.8	39.21	91 (0.9)	2924 (28.0)	7187 (68.9)
≥37 wks	267	1275	19,030	157.27	71.27	124 (0.7)	3908 (20.5)	14,732 (77.4)
Infant days of life at transfer								
<3 days	270	1338	29,318	225.52	108.99	215 (0.7)	7518 (25.6)	21,154 (72.2)
3–7 days	248	698	3062	29.73	12.45	14 (0.5)	448 (14.6)	2514 (82.1)
8–14 days	174	398	1252	16.92	7.24	3 (0.2)	127 (10.1)	1090 (87.1)
15+ days	146	324	1076	16.81	7.58	1 (0.1)	93 (8.6)	956 (88.8)
Medical/surgical transfer								
Medical	267	1120	20,302	189.74	76.04	189 (0.9)	7004 (34.5)	12,882 (63.5)
Surgical	260	702	7394	97.29	28.44	2 (<0.001)	370 (5.0)	6976 (94.3)

[a]Nodes: number of hospitals.

[b]Edges: number of unique directed connections between hospitals.

[c]Transfers: number of acute transports.

[d]Average in/out-degree: average number of incoming/outgoing transports per hospital over the study period.

[e]Destination (intermediate/community/regional): *N* (%) transferred to Level II/III/IV hospitals.

to capture real-world transport patterns. In this context, the greater centralization and lower density and efficiency of the networks for the smallest and youngest infants indicate that these infants are transported to fewer centers, presumably those providing higher-level care, such that many referring hospitals are funneling transports toward a central hub.

Type of transport (medical vs. surgical)

The differing transport patterns between infants transported for medical and surgical reasons similarly corresponds to empiric observations regarding the care needs of these different populations. Infants transported for surgical

Table 3 *P* values for pairwise differences in network metrics for networks constructed from infant attributes.

	Centralization			Density			Efficiency			Modularity		
Birth weight	750–1500 g	1500–2500 g	≥2500 g	750–1500 g	1500–2500 g	≥2500 g	750–1500g	1500–2500g	≥2500 g	750–1500 g	1500–2500 g	≥2500 g
<750 g	<0.001	<0.001	<0.001	0.439	0.063	<0.001	<0.001	<0.001	<0.001	0.018	0.015	0.032
750–1500g		<0.001	<0.001		0.178	<0.001		<0.001	<0.001		0.424	0.52
1500–2500g			<0.001			<0.001			<0.001			0.916
Gestational age	28–32 wks	32–37 wks	≥37 wks	28–32 wks	32–37 wks	≥37 wks	28–32 wks	32–37 wks	≥37 wks	28–32 wks	32–37 wks	≥37 wks
<28 wks	<0.001	<0.001	<0.001	<0.001	0.032	<0.001	0.401	<0.001	<0.001	0.377	<0.001	0.08
28–32 wks		<0.001	<0.001		0.008	<0.001		<0.001	<0.001		0.016	0.356
32–37 wks			<0.001			<0.001			<0.001			0.083
Days of life	3–7 days	8–14 days	15+ days	3–7 days	8–14 days	15+ days	3–7 days	8–14 days	15+ days	3–7 days	8–14 days	15+ days
<3 days	<0.001	<0.001	<0.001	<0.001	0.172	<0.001	<0.001	<0.001	0.926	<0.001	<0.001	<0.001
3–7 days		<0.001	<0.001		0.319	0.001		0.155	<0.001		<0.001	<0.001
8–14 days			0.173			0.001			<0.001			0.004
Transfer type	Medical			Medical			Medical			Medical		
Surgical	<0.001			<0.001			0.878			<0.001		

evaluation and management may need very specific care capabilities that the usual referral center may not be able to provide, as the provision of surgical services is much more limited than neonatal intensive care services, particularly for the most complex surgical problems. The higher centralization and lower density of the surgical transport network align with the experience that these infants are transferred to a small number of central hospitals to provide for their specialized needs. The finding of lower modularity for surgical transfers suggests that many surgical needs may not be met at a regional Level III NICU, and require transport to a higher-level center outside the smaller regional network for this type of care, potentially bypassing centers that are closer, both in the network path and in terms of real-world geography. Further investigation into the transport patterns by type of surgical intervention (for example, long gap esophageal atresia repair or cardiac surgery) is warranted in order to better understand how regionalization for specific conditions could be optimized.

Age at transfer

Networks for infants transported before 3 days of life demonstrate higher modularity, but lower centralization and density, a constellation of findings not paralleled in any of the other attributes studied. The high modularity in the networks for infants transferred early in life, compared to infants transferred later in life, indicates that transfers early in life remain in smaller subnetworks, while low density indicates less interconnection between nodes as common transport routes are frequently followed. However, the lower centralization suggests an overall lack of hub-and-spoke architecture in the network, possibly due to infants early in life being transported to nearby facilities, rather than directly to regional centers. Taken together, these findings suggest that this early transfer group may be dominated by two very different types of transfers: first, very preterm and low birth weight infants born at community NICUs who need rapid transfer to a nearby higher-level referral center; and second, infants with anomalies or other surgical needs that are apparent early in life and require immediate transfer to a specialized centralized facility. In part, this may reflect a growing trend of deregionalization, with more high-risk VLBW and very preterm infants born in the community, a phenomenon for which financial incentives have been partly responsible. Further study of this early transfer group, which comprises the vast majority of neonatal transfers, will shed much-needed light on whether improving regionalization, either in the form of antenatal transports or in reversing the trend of deregionalization, could obviate the need for many of these early transfers.

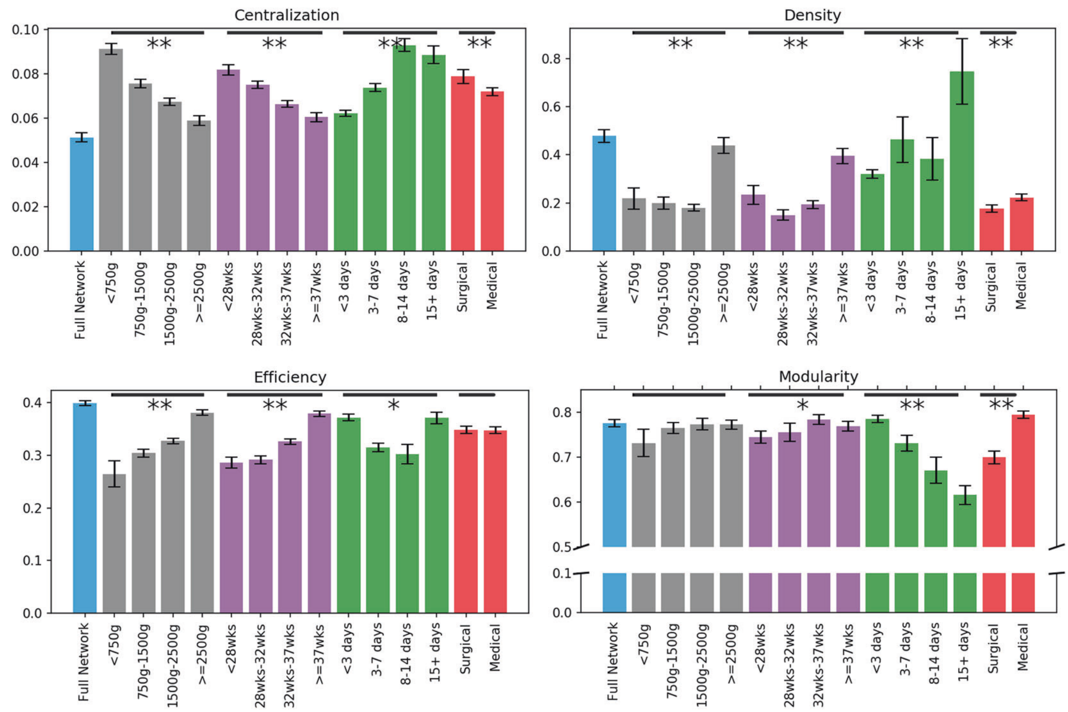

Fig. 2 Network metrics calculated for each group of patient characteristics. Network metrics (centralization, density, efficiency, and modularity) with associated 95% confidence intervals for the entire transport network and all networks based on infant attributes. *Differences significant at $p < 0.05$ level for that attribute. **Differences significant at $p < 0.001$ level for that attribute. Centralization: measure of "hub-and-spoke" organization around important hospitals. Density: proportion of all possible transfer routes between hospitals that were actually used. Efficiency: measure of the shortest (non-geographical) path between any two random hospitals in the network based on existing transfer routes. Modularity: tendency of the network to break into discrete communities of hospitals.

Future directions and limitations

Having established methods for comparing networks between neonatal patient populations, we will be able to further elucidate how nonmedical patient factors, such as race/ethnicity and insurance status, contribute to the shape of neonatal transport networks. This will help identify potential disparities in characteristics of transport networks based on racial/ethnic and socioeconomic factors, which could highlight opportunities for reducing disparities in neonatal care. Furthermore, analyzing networks based on patient diagnosis may provide crucial insights into the clinical interpretation of network analysis as it relates to patient care, and facilitate a better understanding of the real-world implications of network function. Relating the characteristics of neonatal transport networks to patient outcomes and transport quality may illuminate areas for improvement in the way transport networks are composed.

Because the application of network science to neonatal transport networks remains an emerging discipline, there are limitations to its applications. First, our analysis was limited to a single state, raising questions of generalizability to less regionalized areas of the country and world. Second, analysis of transfers as a network is further limited by the ability of the researcher or regulatory agency to obtain accurate care information for each infant longitudinally across multiple institutions. Third, the analysis period in this study is restricted to 2008–2012, due to lack of availability of OSHPD-linked data resources past this time period. We will plan to include any new data that become available in future analyses.

Importantly, as network metrics have not been widely applied to patient transport networks, particularly in neonatology, it is yet unknown which metrics are of most clinical value in describing and studying networks, and which patterns of networks reflect an ideally regionalized system. As optimal patterns of regionalization are partially dependent on regional characteristics, such as geography and payor structure, patterns of metrics that reflect optimal regionalization may be variable by region. Expanding on the foundational work that has been completed to this point, future work will focus on developing composite scores of clinically relevant network metrics to correlate measures of network regionalization with patient outcomes and transport quality. Identifying network characteristics associated with positive clinical outcomes may offer optimization opportunities at different levels of the network. In translating network shape and function into actionable information for clinicians and administrators, network analysis may allow for improvement in the care of infants by improving the networks in which they receive that care.

Author contributions SNK conceptualized and designed the study, drafted the initial manuscript, and reviewed and revised the manuscript. JAFZ and JP conceptualized and designed the study, and reviewed and revised the manuscript. MZ, JR, and DH carried out the analyses, and reviewed and revised the manuscript. CSP conceptualized and designed the study, and critically reviewed the manuscript for important intellectual content. All authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work. Supplementary information is available at JPER's website.

Funding SNK was supported by Grant K08 HS025749 from the Agency for Healthcare Research and Quality. JP and DH were supported by the Stanford Maternal Child Health Research Institute (MCHRI) Grant Program.

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

Ethical approval The study was approved by the institutional review board at Stanford University (protocol #50047). The study was submitted to the institutional review board at Beth Israel Deaconess Medical Center and deemed not human subject research, as all analysis was performed at Stanford University.

References

1. Lupton BA, Pendray MR. Regionalized neonatal emergency transport. Semin Neonatol. 2004;9:125–33.
2. Yeast JD, Poskin M, Stockbauer JW, Shaffer S. Changing patterns in regionalization of perinatal care and the impact on neonatal mortality. Am J Obstet Gynecol. 1998;178:131–5.
3. Paneth N, Kiely JL, Wallenstein S, Marcus M, Pakter J, Susser M. Newborn intensive care and neonatal mortality in low-birth-weight infants: a population study. N Engl J Med. 1982;307:149–55.
4. Gortmaker S, Sobol A, Clark C, Walker DK, Geronimus A. The survival of very low-birth weight infants by level of hospital of birth: a population study of perinatal systems in four states. Am J Obstet Gynecol. 1985;152:517–24.
5. Lasswell SM, Barfield WD, Rochat RW, Blackmon L. Perinatal regionalization for very low-birth-weight and very preterm infants: a meta-analysis. JAMA. 2010;304:992–1000.
6. Rashidian A, Omidvari AH, Vali Y, Mortaz S, Yousefi-Nooraie R, Jafari M, et al. The effectiveness of regionalization of perinatal care services-a systematic review. Public Health. 2014;128:872–85.
7. Neto MT. Perinatal care in Portugal: effects of 15 years of a regionalized system. Acta Paediatr. 2006;95:1349–52.
8. Modanlou HD, Dorchester W, Freeman RK, Rommal C. Perinatal transport to a regional perinatal center in a metropolitan area—maternal versus neonatal transport. Am J Obstet Gynecol. 1980;138:1157–64.
9. Phibbs CS, Bronstein JM, Buxton E, Phibbs RH. The effects of patient volume and level of care at the hospital of birth on neonatal mortality. JAMA. 1996;276:1054–9.
10. Shlossman PA, Manley JS, Sciscione AC, Colmorgen GH. An analysis of neonatal morbidity and mortality in maternal (in utero) and neonatal transports at 24–34 weeks' gestation. Am J Perinatol. 1997;14:449–56.
11. Cifuentes J, Bronstein J, Phibbs CS, Phibbs RH, Schmitt SK, Carlo WA. Mortality in low birth weight infants according to level of neonatal care at hospital of birth. Pediatrics. 2002;109:745–51.
12. Lorch SA, Baiocchi M, Ahlberg CE, Small DS. The differential impact of delivery hospital on the outcomes of premature infants. Pediatrics. 2012;130:270–8.
13. Jensen EA, Lorch SA. Effects of a birth hospital's neonatal intensive care unit level and annual volume of very low-birth-weight infant deliveries on morbidity and mortality. JAMA Pediatr. 2015;169:e151906.
14. Phibbs CS, Baker LC, Caughey AB, Danielsen B, Schmitt SK, Phibbs RH. Level and volume of neonatal intensive care and mortality in very-low-birth-weight infants. N Engl J Med. 2007;356:2165–75.
15. Kaneko M, Yamashita R, Kai K, Yamada N, Sameshima H, Ikenoue T. Perinatal morbidity and mortality for extremely low-birthweight infants: a population-based study of regionalized maternal and neonatal transport. J Obstet Gynaecol Res. 2015;41:1056–66.
16. Mori R, Fujimura M, Shiraishi J, Evans B, Corkett M, Negishi H, et al. Duration of inter-facility neonatal transport and neonatal mortality: systematic review and cohort study. Pediatr Int. 2007; 49:452–8.
17. Bowman E, Doyle LW, Murton LJ, Roy R, Kitchen WH. Increased mortality of preterm infants transferred between tertiary perinatal centres. BMJ. 1988;297:1098–100.
18. Palmer KG, Kronsberg SS, Barton BA, Hobbs CA, Hall RW, Anand KJ. Effect of inborn versus outborn delivery on clinical outcomes in ventilated preterm neonates: secondary results from the NEOPAIN trial. J Perinatol. 2005;25:270–5.
19. Mohamed MA, Aly H. Transport of premature infants is associated with increased risk for intraventricular haemorrhage. Arch Dis Child-Fetal Neonatal Ed. 2010;95:F403–7.
20. Arora P, Bajaj M, Natarajan G, Arora NP, Kalra VK, Zidan M, et al. Impact of interhospital transport on the physiologic status of very low-birth-weight infants. Am J Perinatol. 2014;31:237–44.
21. Helenius K, Longford N, Lehtonen L, Modi N, Gale C, Neonatal Data Analysis U, et al. Association of early postnatal transfer and birth outside a tertiary hospital with mortality and severe brain injury in extremely preterm infants: observational cohort study with propensity score matching. BMJ. 2019;367:l5678
22. Kunz SN, Zupancic JA, Rigdon J, Phibbs CS, Lee HC, Gould JB, et al. Network analysis: a novel method for mapping neonatal acute transport patterns in California. J Perinatol. 2017;37:702–8.
23. Das K, Samanta S, Pal M. Study on centrality measures in social networks: a survey. Soc Netw Anal Min. 2018;8:1–13.
24. Benzi M, Klymko C. On the limiting behavior of parameter-dependent network centrality measures. SIAM J Matrix Anal Appl. 2015;36:686–706.
25. Katz L. A new status index derived from sociometric analysis. Psychometrika. 1953;18:39–43.
26. de Laat M, Lally V, Lipponen L, Simons RJ. Investigating patterns of interaction in networked learning and computer-supported collaborative learning: a role for social network analysis. Int J Comp-Supp Coll. 2007;2:87–103.
27. Pasquaretta C, Leve M, Claidiere N, van de Waal E, Whiten A, MacIntosh AJJ, et al. Social networks in primates: smart and tolerant species have more efficient networks. Sci Rep. 2014; 4:7600.
28. Latora V, Marchiori M. A measure of centrality based on network efficiency. New J Phys. 2007;9:188.

29. Latora V, Marchiori M. Efficient behavior of small-world networks. Phys Rev Lett. 2001;87:198701.
30. Yang Z, Algesheimer R, Tessone CJ. A comparative analysis of community detection algorithms on artificial networks. Sci Rep. 2016;6:30750.
31. Fortunato S. Community detection in graphs. Phys Rep. 2010;486:75–174.
32. Newman MEJ. Modularity and community structure in networks. Proc Natl Acad Sci U S A. 2006;103:8577–82.
33. Pons P, Latapy M. Computing communities in large networks using random walks. Lecture Notes in Computer Science, vol. 3733. 2005. p. 284–93.
34. Profit J, Gould JB, Bennett M, Goldstein BA, Draper D, Phibbs CS, et al. The association of level of care with NICU quality. Pediatrics. 2016;137:e20144210.
35. Gould JB, Marks AR, Chavez G. Expansion of community-based perinatal care in California. J Perinatol. 2002;22:630–40.
36. Odén A, Wedel H. Arguments for Fisher's permutation test. Ann Stat. 1975;3:518–20.
37. Fisher RA. Statistical methods for research workers. In: Breakthroughs in statistics. Springer; 1992. p. 66–70.
38. Simpson SL, Lyday RG, Hayasaka S, Marsh AP, Laurienti PJ. A permutation testing framework to compare groups of brain networks. Front Comput Neurosci. 2013;7:171.
39. Efron B. Nonparametric estimates of standard error—the jackknife, the bootstrap and other methods. Biometrika. 1981;68:589–99.
40. Hagberg A, Swart P, S Chult D. Exploring network structure, dynamics, and function using NetworkX. Los Alamos National Laboratory (LANL), Los Alamos, NM (United States); 2008.
41. Csardi G, Nepusz T. The igraph software package for complex network research. InterJournal, Complex Syst. 2006;1695:1–9.
42. Rives AW, Galitski T. Modular organization of cellular networks. Proc Natl Acad Sci U S A. 2003;100:1128–33.