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Modeling Travel Impedance to Medical Care for Children with Birth Defects Using Geographic Information Systems

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Abstract

BACKGROUND—Children with birth defects may face significant geographic barriers accessing medical care and specialized services. Using a Geographic Information Systems–based approach, one-way travel time and distance to access medical care for children born with spina bifida was estimated.

METHODS—Using 2007 road information from the Florida Department of Transportation, we built a topological network of Florida roads. Live-born Florida infants with spina bifida during 1998 to 2007 were identified by the Florida Birth Defects Registry and linked to hospital discharge records. Maternal residence at delivery and hospitalization locations were identified during the first year of life.

RESULTS—Of 668 infants with spina bifida, 8.1% (n = 54) could not be linked to inpatient data, resulting in 614 infants. Of those 614 infants, 99.7% (n = 612) of the maternal residential addresses at delivery were successfully geocoded. Infants with spina bifida living in rural areas in Florida experienced travel times almost twice as high compared with those living in urban areas. When aggregated at county levels, one-way network travel times exhibited statistically significant spatial autocorrelation, indicating that families living in some clusters of counties experienced substantially greater travel times compared with families living in other areas of Florida.

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CONCLUSION—This analysis demonstrates the usefulness of linking birth defects registry and hospital discharge data to examine geographic differences in access to medical care. Geographic Information Systems methods are important in evaluating accessibility and geographic barriers to care and could be used among children with special health care needs, including children with birth defects.

Keywords

birth defects; spina bifida; medical care; geocoding; GIS; network modeling; travel distance; travel time

INTRODUCTION

Although it is known that children with special health care needs can face significant barriers to accessing health care services compared with children without special needs (McPherson et al., 2004; Newacheck and Kim, 2005; Skinner and Slifkin, 2007; Strickland et al., 2009; Chiri and Warfield, 2012; Romaire et al., 2012), little is known about geographic barriers to care for children with birth defects, a subset of children with special health care needs.

Travel impedance, such as travel time and distance, can play an important role in the utilization of health care services (Lovett et al., 2002) and survival of children with special health care needs. A few studies using birth defects surveillance data have examined location of services and its effect on survival and health service utilization (Case et al., 2008; Cassell et al., 2009; Fixler et al., 2012). Using Texas Birth Defects Registry data for infants born in 1999 to 2004 with major structural defects and chromosomal anomalies, Case et al. (2008) found that 14% of those infants were living 31 to 100 miles from a pediatric genetic service provider, and for 4% of these infants, the closest service provider was located more than 100 miles away, due to the limited number of locations providing genetic services. Using North Carolina birth defects and Medicaid data for 1995 to 2002, Cassell et al. (2009) found significant geographic differences in the receipt of timely primary cleft surgical repair for children with orofacial clefts. Children living in metropolitan areas were more likely to receive primary cleft surgical repair within 18 months of life, which was possibly due to a greater availability of hospitals in those areas (Cassell et al., 2009). Using 1996 to 2003 Texas birth defects registry data, Fixler et al. (2012) reported that distances from maternal address at time of delivery to the nearest hospital did not influence first year survival of infants with congenital heart defects.

While findings from these studies may be useful for informing decisions on the location of additional hospitals and specialty centers, these studies had three important limitations. First, each of these studies assumed that children received health care services at the closest provider, which may not be the case for several reasons, including complexity of the medical condition(s), parental employment status, child's age, and referral to services. Second, the use of Euclidean distance to estimate proximity underestimates the true distance traveled because that metric fails to take into account the underlying transportation infrastructure (e.g., roads) used when traveling between two locations. Third, these studies

did not examine travel time, which may be more important to parents and caregivers of children with special health care needs, including birth defects, than travel distance. Underestimating the travel distance can lead to errors when computing travel impedance, especially for individuals living in rural and suburban areas. Although the travel distance can be approximated by a Manhattan metric in urban areas, the true travel impedance may be underestimated in rural areas when using Euclidean distance (Apparicio et al., 2008; Jones et al., 2010; Gutiérrez and García-Palomares, 2011).

Modeling travel impedance for children with birth defects can be conducted through the use of a Geographic Information Systems (GIS), which is a system that can manage, analyze, and visualize spatial data. Recent advances in GIS have facilitated geocoding and the modeling of road networks to estimate travel impedance more accurately (Frizzelle et al., 2009; Delamater et al., 2012), which can be used to examine geographic access to medical care (Delmelle et al., 2011). This information can be important for health services researchers, public health officials, and health care providers in evaluating the need for additional hospitals and specialty centers.

Geocoding, a procedure that converts text-based information about locations (e.g., addresses and ZIP code) into geographic coordinates (Jacquez, 2012), is often used in GIS-based methods. Its success mainly relies on the completeness of the addresses and on the quality of local and regional street road network files (Krieger et al., 2001; Cayo and Talbot, 2003; Zandbergen, 2008).

Aside from geocoding (Forand et al., 2002; Gilboa et al., 2006, Strickland et al., 2007), GIS techniques have been used in birth defects research in a variety of ways, such as determining prevalence, risk factors (e.g., socioeconomic status and living near hazardous sites), access to health care, and mapping the spatial distribution of birth defects (Rushton and Lolonis, 1998; Wasserman et al., 1998; Siffel et al., 2006; Gardner et al., 2007; Case et al., 2008; Langlois et al., 2009a,b; Luben et al., 2009; Messer et al., 2010; Wang et al., 2010a; Root et al., 2011; Fixler et al., 2012; Colvin et al., 2013).

Aday and Andersen (1974) suggested that “access” needed to be measured in terms of whether the population with health care needs is able to enter the medical system, a concept also known as “realized” access (Khan and Bhardwaj, 1994). In “realized” access, spatial or geographic barriers to health services play an important role in timeliness of services and health outcomes (Guagliardo, 2004). Linking birth defects surveillance information with health services data, medical records, hospital discharge data, and vital statistics records provide spatial data for use in a GIS analysis. The linkage of these data sources makes it possible to estimate travel impedance for each hospitalization, which is the purpose of our study. Thus, the focus of our study is the spatial aspect of “realized” access to health services.

Identification of barriers to care, including geographic barriers, were recognized as important public health research priorities for several types of birth defects at several meetings of experts convened by the Centers for Disease Control and Prevention (Yazdy et al., 2007; Rasmussen et al., 2008a,b). The U.S. Department of Health and Human Services’

Healthy People 2020 cites increase in access to care in their Maternal-Infant-Child Health (MICH) goals. MICH Goal 30.2 states programs will increase the percentage of children with special health care needs who have access to a medical home, and the objective of MICH Goal 31 is to increase the proportion of children with special health care needs who receive care in family-centered, coordinated, and comprehensive systems (U.S. DHHS, 2012).

The development of a GIS-based methods approach is essential to better understanding geographic disparities in access to care for children with birth defects and to address these public health priorities. We present an innovative GIS-based approach to calculate travel impedance to access medical care for infants with spina bifida (SB) and identify geographic variations in travel impedance to access hospital care for these infants, using a state-wide, population-based birth defects surveillance program and hospital discharge data.

METHODS

Description of Data Sources: Birth Defects Surveillance and Hospital Discharge Data

We used the Florida Birth Defects Registry (FBDR), a state-wide, population-based, passive surveillance system to identify infants with SB without anencephaly, using the International Classification of Diseases, 9th revision, Clinical Modification codes 741.00–741.93. These infants were born January 1, 1998, to December 31, 2007. This study sample included infants who died at any point during the first year of life. Approximately 1,500 infants with SB are born every year in the United States (Parker et al., 2010). In Florida, approximately 70 infants with SB were born annually during our study period (Florida Department of Health, 2010).

The FBDR contains information from multiple health care databases, including hospital discharge data and vital statistics (Salemi et al., 2011, 2012). The FBDR includes live-born infants with birth defects whose mothers were residents of Florida at the time of the infant's birth and excludes infants with birth defects who were adopted and those whose mothers delivered out-of-state (Salemi et al., 2011, 2012).

One of the primary sources of identification of infants with birth defects, including SB, for the FBDR is the Florida Agency for Health Care Administration, which includes hospital discharge data (Salemi et al., 2011). We linked infants with SB identified by the FBDR to hospital discharge data for 1998 to 2008 to ensure at least one year of hospital discharge data for each infant. Using the maternal residential address at delivery from the FBDR, the Florida Department of Health (FDOH) conducted a geocoding process to determine the geographic coordinates of infants. For this study, only hospitalizations initiated within the first year of life (infancy) for infants with SB without anencephaly were analyzed.

We did not include all Florida hospitals in our analysis because some Florida hospitals do not report data to the Florida Agency for Health Care Administration, including long- and short-term psychiatric hospitals, inpatient residential treatment and rehabilitation facilities, and military hospitals (Agency for Health Care Administration, 2013). The 227 Florida

hospitals used by infants with at least one major birth defect during the study period reflected hospitals most likely to be used by infants with SB for hospital care.

Geocoding Process

Accurate geocoding is necessary to determine geographic coordinates of infants and hospitals where children received care during the first year of life. Figure 1 illustrates the protocol used to geocode the maternal residential address at delivery of infants with SB. We adopted a multi-stage strategy, with an initial, automated geocoding phase followed by an improvement phase (McElroy et al., 2003; Yang et al., 2004). During the first phase, the FDOH used *MapMaker Plus*TM, a commercial geocoding environment, to geocode addresses at the street level. We geocoded the maternal residential address at delivery for infants with SB who had at least one hospitalization record during infancy. For addresses that could not be geocoded at the street level, FDOH attempted to geocode those addresses at the ZIP-code level using *Instant Geocoder*TM.

In the second phase, we combined those addresses that were either geocoded at the ZIP-code level by *Instant Geocoder*TM or addresses that were not geocoded at all. Additional address information from the infant's mother was used from the infant's birth certificate and hospital discharge data (e.g., mother's mailing address and mother's residential ZIP-code). We built a customized address locator in the ArcGIS environment, a commercial GIS (ESRI, Redlands, CA), capable of integrating U.S. Census Bureau 2010 street TIGER files. The 2010 U.S. Census Bureau road network dataset is more robust and complete than the one published for the year 2000. Using the new address locator, we first attempted to improve the geocoding procedure at the street level using maternal residential addresses at birth, then maternal mailing addresses. If both steps failed, we used maternal residential ZIP code. All Florida hospitals (n = 227) where infants were hospitalized during 1998 to 2008 were geocoded with *BatchGeo*TM at the street level.

Road Network Modeling

In GIS, a road network is modeled as a graph of nodes connected together by edges (also termed road segments). The distance to traverse an edge is defined by its length, while the time to travel that edge is its length divided by its maximum allowed travel speed. Modeling travel between locations should ideally incorporate speed limits, honor one-way restrictions, and reflect connectivity among roads (Miller and Shaw, 2001; Cromley and McLafferty, 2011).

For this study, we used the 2007 Florida Department of Transportation road network and considered both travel time and distance as measures of travel impedance. The GIS-based road network incorporated six different road types: interstates, U.S. routes, county roads, state roads, local roads, and ramps. For each of the six different road types, a topological rule was implemented to guarantee that no road segments would remain unconnected to another road segment at one or both endpoints. We enforced the "one-way" rule, which allowed travel along a road segment in one direction but prevented it in the reverse direction. The same rule was implemented for modeling directionality on highway ramps [see Fig. 2a and b; (Peuquet, 1984)]. Our customized GIS-based road network was built in

ArcGIS 10.0, and all topological rules were implemented in the Python programming language.

Similar to Delamater et al. (2012), we tested the concordance of travel times and distances for generated one-way routes within our customized GIS-network to those obtained from Google Maps™, using the Google Maps™ Library for Python. To compare these two networks, 3,591 routes were selected across Florida, covering a wide range of Euclidean distances (one-way mean: 181.17 miles; one-way range: 0.01–563.59 miles). Travel distances in our GIS-based road network strongly agreed with travel distances for the same routes in Google Maps™ ($r^2 = 0.95$ for urban to rural routes; $r^2 = 0.94$ for rural to urban routes; and $r^2 = 0.95$ overall). We also compared the underestimation in one-way travel distances using a Euclidean metric with a network distance metric. Strong underestimations were observed in rural areas (particularly the Panhandle), indicating that the network distance metric provided a more accurate measure of true travel impedance.

Categorization of Geographic Regions

The U.S. Census Bureau provides a large number of spatial data, such as geographic boundaries for the United States and each state. In this study, the U.S. Census Bureau's state, urban and county boundary data from 2000 were used for visualization purposes and aggregation of network time and distances. The year 2000 was used because of our selected birth cohort of 1998 to 2007. Geographic regions were categorized according to the U.S. Census Bureau and included urban areas, which have a population above 50,000 individuals, urban clusters, which have a population between 2,500 and 50,000 individuals, and nonurbanized (rural) areas, including all areas with a population less than 2,500 individuals (U.S. Census Bureau, 2001, 2010).

Estimating Travel Impedance

Using all hospitalizations initiated during the first year of life, the average travel impedance for each infant was computed as the sum of the one-way travel for each infant's hospitalization divided by the total number of hospitalizations for that infant. In Eq. 1, the term X_{ij} is a positive integer variable ($X_{ij} \in \mathbb{Z}^+$) reflecting the number of visits for each infant ($i, i = 1, 2, \dots, M$) to a particular hospital ($j, j = 1, 2, \dots, N$). N is the set of all hospitals that are used at least once by an infant with a particular birth defect for whom the maternal residential address at delivery was successfully geocoded. In our study, the term "utilization" refers to all hospitals where at least one infant had a hospitalization initiated during the first year of life. The term $d_{ij;k}$ is the one-way travel impedance from the maternal residential address at delivery (i) to a hospital (j), which can be estimated in a commercial GIS environment, using the Dijkstra shortest-path algorithm (Miller and Shaw, 2001). The subscript (k) refers to the type of impedance (time or distance). The Dijkstra algorithm finds the optimal combination of road segments while minimizing the accumulated impedance, identifying the most direct route. Figure 2c indicates that the distance metric used to minimize travel impedance greatly affects the route of travel.

The utilization rate U_j of each hospital j was computed as the total number of visits at hospital j , divided by the total number of visits for the entire state of Florida for our study population [see Eq. 1 for an illustration].

$$U_j = \frac{\sum_{i=1}^M X_{ij}}{\sum_{i=1}^M \sum_{j=1}^N X_{ij}} \forall j, \quad j=1 \dots N \quad (1)$$

We estimated excess travel, which is the one-way travel difference between the closest hospital and the hospital where the hospitalization occurred. Higher values of excess travel may be indicative of parents traveling greater distances or longer times than if they had received care at the closest hospital. Assuming that d_i^* is the one-way travel impedance to the closest hospital, the average excess travel \overline{R}_i for each infant i is defined in Equation 2 as:

$$\overline{R}_i = \frac{\sum_{j=1}^N (d_{ij} - d_i^*) X_{ij}}{\sum_{j=1}^N X_{ij}}, \quad i, i=1 \dots M \quad (2)$$

Due to skewness of the results and multiple hospitalizations for infants with SB during the first year of life, we reported one-way mean and median travel distances and times per infant with SB per hospitalization.

Spatial Patterns and Geomasking Process

The Moran's I statistic (Moran, 1950) is used to test for spatial association among spatially adjacent counties and ranges from -1 to 1 . A positive Moran's I indicated that values of one-way travel impedance among adjacent geographic units tend to be similar.

For confidentiality purposes, the geocoded location of infants with SB was geomasked by shifting the coordinates of the maternal residential addresses at delivery. The process of geomasking is well documented in the literature (Kwan et al., 2004).

Due to the potential presence of spatial autocorrelation, the local Moran's I ("LISA") (Anselin, 1995) was used to identify and map those clusters of similar values. The LISA-statistic measures the association between travel impedance for a particular county and travel impedance for adjacent counties. The statistic is particularly useful to locate a region that has an unusually high concentration of travel impedance (Cromley and McLafferty, 2011).

RESULTS

Geocoding and Road Network Modeling

We identified 668 infants with SB without anencephaly. Of the 668 infants, 54 could not be linked to inpatient hospital discharge data, resulting in 614 infants with SB (Radcliff et al., 2012). This resulted in 614 unique infants who linked to at least one hospitalization record during the first year of life, of whom, 90.7% ($n = 557$) of addresses were successfully geocoded at the street level by the FDOH. The remaining addresses, for which no

coordinates could be found at the street level, were then geocoded at the ZIP-code level, which resulted in 7.3% (n = 45) of infants being successfully geocoded. During this first phase, 2.0% of addresses (n = 12) could not be geocoded. The geocoding rate was improved in a second phase, resulting in 91.7% (n = 563) of addresses that matched at the street level, 8.0% (n = 49) at the ZIP-code level (n = 20 or 3.2% in rural areas and n = 29 or 4.7% in urban areas), and 0.3% (n = 2) that could not be geocoded at all. In summary, of these 614 infants, 612 (99.7%) of the infants' maternal residential address at delivery were successfully geocoded. Figure 1 illustrates the geocoding process used for our study population.

The spatial distribution of the 612 infants with SB who were successfully geocoded is shown in Figure 3a, which indicated a greater number of infants living in urban areas, such as Jacksonville, Miami, Orlando, Pensacola, St. Petersburg/Tampa, and in the vicinity of major interstate highways, while lower concentrations were noted in rural areas.

Figure 3b illustrates the location of the hospitals used at least once by infants with SB. During the study period (1998–2008), 1,629 hospitalizations (inpatient records) for infants with SB were reported. These hospitalizations occurred at 108 of 227 (47.6%) hospitals used by infants with major birth defects during 1998 to 2008.

In Figure 3c, each line represents a hospitalization and links the infant's maternal address at delivery to the hospital facility where a hospitalization was initiated during infancy. Figure 3c revealed several interesting patterns. First, infants were not always hospitalized at facilities that were the closest to their maternal residence. Second, hospitals located in Gainesville, Orlando, St. Petersburg/Tampa, Miami, and West Palm Beach were more frequently used than other hospitals. Third, several infants living in the Pensacola region were hospitalized in Gainesville, which impacted both one-way travel distance and time.

Theoretical One-way Travel Time to Hospitals

In Figure 4a, the theoretical one-way travel time to hospitals used at least once by infants with SB was computed and mapped. This map illustrates the service area of all used hospitals for hospitalizations that were initiated during infancy. A darker blue color denotes regions where the closest hospital could be accessed in a 30 min drive time or less. Lighter blue colors indicate a longer travel time to the closest facility, suggesting a lower level of geographic accessibility. Figure 4b aggregates the theoretical travel time to the county level to facilitate the visual comparison with Figures 4c and d. The color was selected based on the service area travel time category that is predominant within each county, by spatial overlay. Families living in urban areas and interstate corridors experienced better geographic access to hospitals.

Estimated One-way Travel Impedance (Time and Distance) to Hospitals

The estimated one-way time traveled, aggregated by county, was reported and mapped in Figure 4c. We observed geographic differences in travel time between urbanized areas, urban clusters and nonurbanized (or rural) areas. The average one-way time traveled to hospitals for families of infants with SB was estimated to be 45.1 min (median: 25.9 min; range: 2.4–494.1 min), with an average one-way travel distance of 34.5 miles (median: 18.1

miles; range: 1.2–403.9 miles). Over half of these families (56.4%; $n = 345$) traveled an average of 30 min or less for their infants' hospitalizations during the first year of life (Table 1). The distribution of the one-way travel times showed exponential decay, but a second peak appeared for longer travels.

One-way network travel time for hospitalizations were aggregated and mapped at the county level, and these results are shown in Figure 4c. The county scale was used because too few observations were reported at finer scales (e.g., census tracts, census block groups, or census blocks). Families of infants living in counties surrounding Jacksonville, Gainesville, Orlando, St. Petersburg/Tampa, and Miami experienced much shorter one-way travel times (< 30 min) than families of infants living in rural counties. Infants living in counties located near urban areas experienced a much shorter travel time, with the exception of Escambia County, which includes the city of Pensacola.

Graduated symbols depict the variation in hospital utilization in Equation 2 and Figure 4c. Larger dots represent greater numbers of hospitalizations that occurred at that particular hospital within the study period and by the study population. Examples of hospitals with higher utilization include those in Gainesville, Orlando, St. Petersburg/Tampa, Pensacola, Miami, and Jacksonville.

In Table 2, we summarized the estimated one-way travel times among urbanized, urban clusters, and nonurbanized areas. Families with infants living in urban areas ($n = 480$) experienced a much lower average one-way travel time to hospitals than families living in nonurbanized areas (rural areas) ($n = 87$), 38.3 and 68.1 min, respectively, while infants located in urban clusters ($n = 45$) had an average one-way travel time higher than the other two groups (73.9 min). Similarly, median one-way travel times for families living in urban areas were lower compared with families living in nonurban areas, 22.2 and 46.6 min, respectively.

Spatial Variation in One-way Travel Times and Distances

We show the excess travel results in Figure 4d. Small values (light orange in Fig. 4d) reflect infants hospitalized at the closest hospital, while larger values (dark brown in Fig. 4d) were indicative of infants having to travel greater distances for hospitalizations. The differences were smaller in counties surrounding metropolitan cities (e.g., Orlando, Gainesville, St. Petersburg/Tampa, and Miami).

We tested whether clusters of counties experienced travel impedance significantly higher than their neighbors as well as other regions in the state by means of spatial statistics. Results indicated a strong positive spatial autocorrelation, when one-way travel time and distances were aggregated at the county level (Table 3), suggesting that families in nearby counties experienced similar, high travel impedance, and that those patterns were not random. We found a cluster of high average network times (hot spots) in the counties located between Pensacola and Tallahassee (Fig. 4d). This was consistent with observations comparing theoretical and estimated one-way travel times (Figs. 4b and c).

DISCUSSION

The GIS methods presented in this study illustrates the value of GIS in providing a better understanding of spatial accessibility to medical care for children with birth defects. By modeling travel impedance for these infants, we identified geographic variations in spatial accessibility and hospital utilization. We illustrated our GIS methods for infants with SB born in Florida from 1998 to 2007. On average, their families experienced 45 min in one-way travel time and 34 miles in one-way travel distance for hospitalizations during the infant's first year of life.

When results were aggregated at the county level, differences in travel time were identified. Families living in counties between Pensacola and Tallahassee exhibited longer travel times, despite hospitals located closer to the maternal residential address at delivery. This is an important finding as the cluster of high travel time in that region may have gone unnoticed with a Euclidean distance metric, due to distance underestimation. Families may not take their children to the closest hospital for many reasons, including availability of hospital beds, types of services provided at that hospital, insurance coverage, referral, preference of primary care physician and/or specialists, parental occupation or employment status, and maternal age and education. These factors can influence where children with special health care needs, including children with birth defects, receive care (Skinner and Slifkin, 2007; Case et al., 2008; Cassell et al., 2009, 2012; Fixler et al., 2012; Pinto et al., 2012).

Compared with infants of families living in urbanized areas, infants located in urban clusters or nonurbanized areas experienced one-way travel time twice as high. One explanation may be in the location of hospitals used by the study population: of the 108 hospitals used, 90.7% (n = 98) were located within urbanized areas, while the remaining 9.3% (n = 10) hospitals were located within urban clusters. This disparity may be explained because most of the infants living outside urbanized areas have to drive to the nearest city to seek hospital care. As discussed by Hine and Kamruzzaman (2012), the two-peak distribution found in our results is common, partly because high income families may travel longer distances to obtain the care they need for their infant. In addition, higher hospital utilization rates in urban areas may be indicative of a higher level of care or greater demand for hospitalizations in areas where population densities are greater and more high level care hospitals exist.

Our results are congruent with those of Case et al. (2008) and Fixler et al. (2012) that geographic barriers to access health services can be important. Information on geographic barriers to care may allow program planners, public health officials, and/or health services researchers to target underserved areas and may improve health service delivery. Using our proposed GIS-methods customized network, researchers could simulate the reduction in travel time and distances when adding a new hospital to the existing network by means of location modeling (Murawski and Church, 2009).

Assumptions and Limitations

This study relied on several assumptions that may affect the validity of our proposed GIS-modeling. First, all the distances between the maternal residential address at delivery and hospitalizations were assumed to be traveled by car and not by public transportation, such as

by bus or subway. Second, the route between the two locations was assumed to be the fastest (and shortest) one, which may not reflect reality. Parents may prefer routes more familiar to them or combine their trips for other purposes (so-called trip-chaining) or may stop by relatives' houses for support. The time of day and specific weekday during which the trip is carried out may impact travel time (e.g., route congestion, road construction and rush-hour traffic, which could all impact traffic patterns). Our measure of travel impedance reflects one-way travel time and distance from maternal residential address at delivery to the hospital where care was received and does not include reverse travel. Thus, our estimates are most likely underestimates of true travel impedance. Third, we assumed that the point of origin of each travel was the maternal residential address at delivery (i.e., assumed infants lived with their mothers). Fourth, we also made the assumption that the maternal residential address remained constant over the first year of life. This is probably a good assumption for infancy, but may not be a good assumption for a longer period of time (e.g., throughout childhood). We are unaware of any published literature about residential mobility for families of children with birth defects after the infant's birth.

Our study had several limitations. First, out-of-state hospitalizations were not considered in this study because hospital discharge data were only available for hospitalizations that occurred in Florida. If families traveled out-of-state for their infants' hospitalizations, then this may have increased or decreased travel time and distance. Thus, our results probably underestimate or overestimate the "true" travel time and distance to access medical care for families who sought care in hospitals out-of-state. Second, infants who died during infancy were included in our study, which may have impacted travel time and distance because they would have had fewer hospitalizations. Third, the impact of geocoding uncertainty needs to be estimated, especially for those infants geocoded at the ZIP-code level. In our study, although only 3.2% (n = 20) of infants were geocoded at the ZIP-code level in rural areas, ZIP-code geocoding may introduce bias in our estimation of travel impedance. Population or socioeconomic status-weighted geoimputation may improve the accuracy of the travel impedance estimates (Henry and Boscoe, 2008). Fourth, because this was a descriptive study, focusing on an innovative GIS-modeling approach for birth defects, such as SB, we did not control for certain characteristics, such as health insurance type, socioeconomic status or any other potential confounding factors that could have influenced our results. Fifth, we examined travel time and distance of infants with an International Classification of Diseases, 9th revision, Clinical Modification code indicating SB, regardless of the reason for the hospitalization. This decision could have over- or underestimated our results. The extent to which this biased our results is not known. Subsequent studies are planned that will explore travel time and distance for hospital admissions specifically related to SB and its comorbidities, such as treatment of urinary tract infections or shunt revisions. Another limitation of our work is that we did not examine hospital nursery level of care. The hospital nursery level of care designation can serve as a proxy for the range of services provided in that hospital unit. We plan to conduct a multivariable analysis in a future project to explore the impact and association of hospital nursery care level, as well as other individual (i.e., maternal and child) and system (e.g., payer status) characteristics, on travel time and distance. Additionally, the results obtained in this study are state-specific and may not be generalizable to other states. Lastly, to identify infants with SB, we used a passive birth

defects surveillance system. Although passive birth defects surveillance systems are widely used throughout the United States, they often do not clinically verify the birth defect diagnosis by means of a medical record or review by a clinician. Passive surveillance systems may lead to under-reporting or over-reporting of infants with birth defects (Lary and Edmonds, 1996; Parker et al., 2010; Salemi et al., 2011, 2012; Holmes and Westgate, 2012). A more thorough investigation of all these limitations is necessary to better understand geographic disparities in access to care for children with birth defects.

Strengths

Despite these limitations, our methods and study demonstrated several strengths. First, by developing an accurate geocoding procedure and using a multi-stage strategy, we were able to increase the number of geocoded maternal residential address at delivery from 98.0% (90.7 + 7.3) to 99.7% (91.7 + 8.0), although 8.0% remained geocoded at the ZIP-code level. Second, the GIS-based model to determine travel times and distances for infants with spina bifida to hospitalizations revealed significant one-way travel differences in different geographic areas of Florida, allowing us to detect regions of similar travel times and distances. Third, the use of network time and distance was an improvement upon previous studies that predominately used Euclidean distances. Fourth, we incorporated topology rules on the road network, which resulted in realistic (shortest) route choices. Fifth, in our study, we estimated one-way travel time and distance to hospitalizations (location where services were actually received), as well as excess one-way travel time and distance, which allowed us to map imbalances in geographic accessibility to health care. Sixth, although we illustrated our GIS-based methodology for infants born with SB, the methodology can be applied to infants with other birth defects. Finally, this study included a unique combination of population-based, state-wide birth defects registry data linked to hospital discharge data and used rigorous GIS methods.

Recommendations and Implications

In 2007, a survey was conducted to assess state birth defects surveillance programs capacity to geocode maternal residence and to identify barriers to geocoding birth defects data (Wang et al., 2010b). Of the 74% (n = 39/53) of state birth defects surveillance program that responded, 97% collected maternal residential address at delivery. Many state birth defects surveillance programs were not geocoding these data, and of those that were geocoding, 53% were geocoding to the street address level (Wang et al., 2010b).

Based on these results of birth defects surveillance program's capacity to geocode maternal residence and our results, we recommend the following areas for future research for the GIS and birth defects fields. First, individual and system factors should be examined to explain the potential disparities in travel time and distance. Second, understanding the effect of socioeconomic status on travel time and distance is important, such as determining whether parents with a higher socioeconomic status (i.e., higher income and/or higher education attainment) tend to drive longer distances to receive care. Third, a thorough investigation of factors that influence decisions to use one hospital over another is important, for example, proximity to residential location, family, referrals, health insurance type, type of hospital (tertiary vs. community), birth defect type, and presence of other comorbidities. Fourth, it

may be important to assess travel impedance by various infancy periods, such as the birth hospitalization, neonatal, and postneonatal periods. This is because greater travel impedance may be experienced during the birth hospitalization at a higher level delivery hospital and then care may be facilitated at a community hospital closer to the home after the birth hospitalization. Such utilization would have higher travel impedance during the birth hospitalization and lower travel impedance as the infant gets older. Finally, it would be valuable to use the computed GIS-network measures in models of accessibility, which takes more aspects of access into account, such as capacity of hospitals and demand population (e.g., two-step floating catchment area) (Luo and Wang, 2003). Using these models might give a more complete view of the spatial accessibility for children with special health care needs, including children with birth defects. The combination of GIS methods and birth defects registry data may improve our understanding of hospital resource utilization and disparities in accessing care for these populations.

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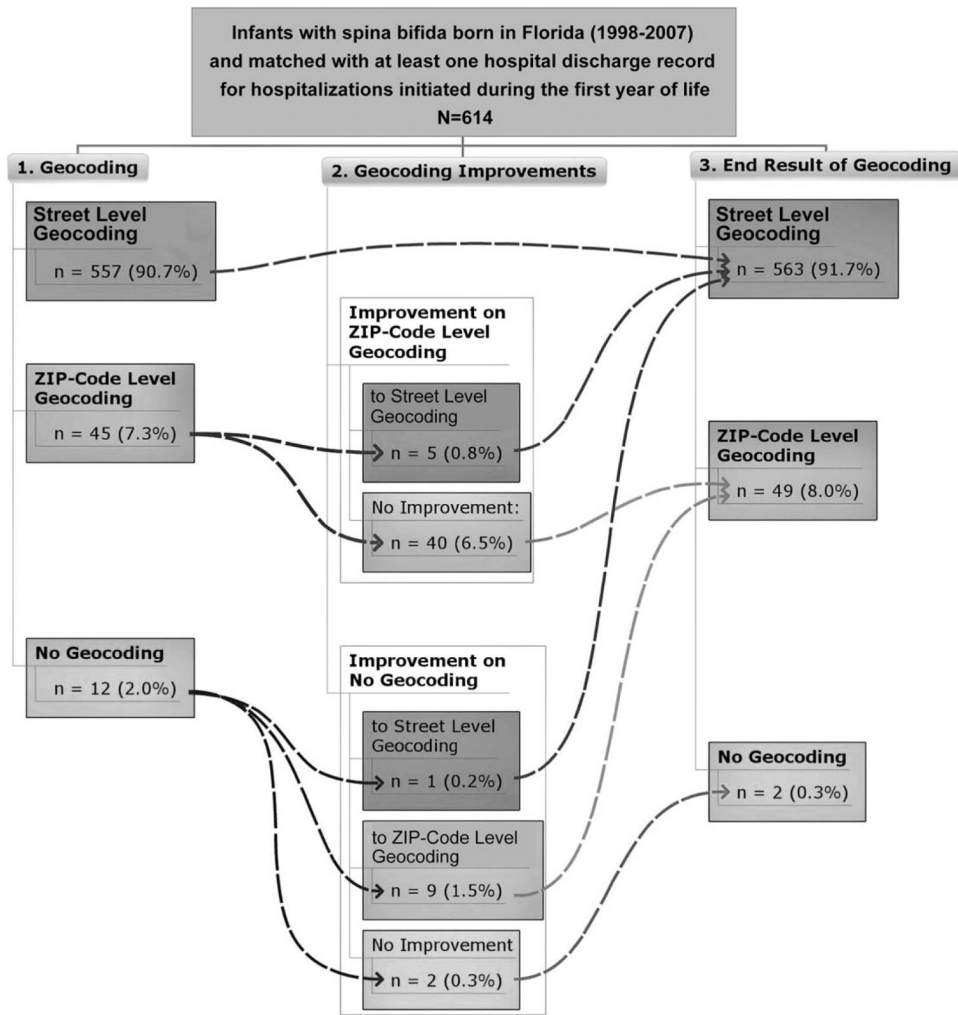


Figure 1. Flowchart of the two steps performed for the geocoding procedure for infants with spina bifida born in Florida, 1998 to 2007. The percentage is relative to the total number of infants with spina bifida having at least one hospital discharge record for hospitalizations initiated during the first year of life (n = 614).

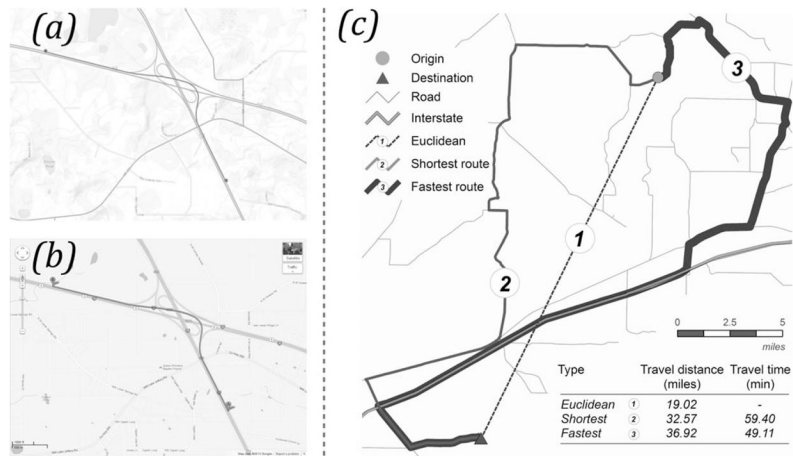
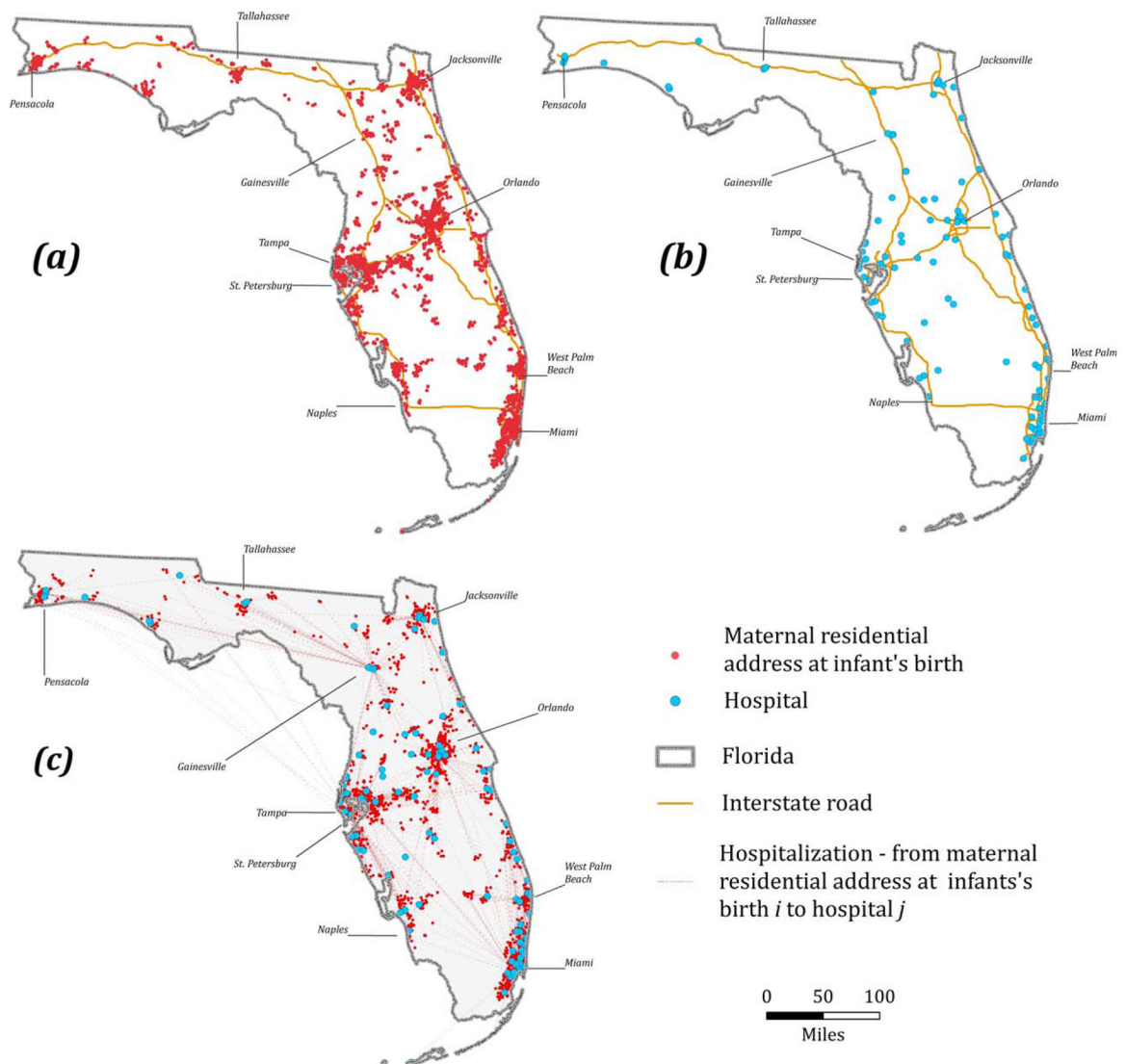


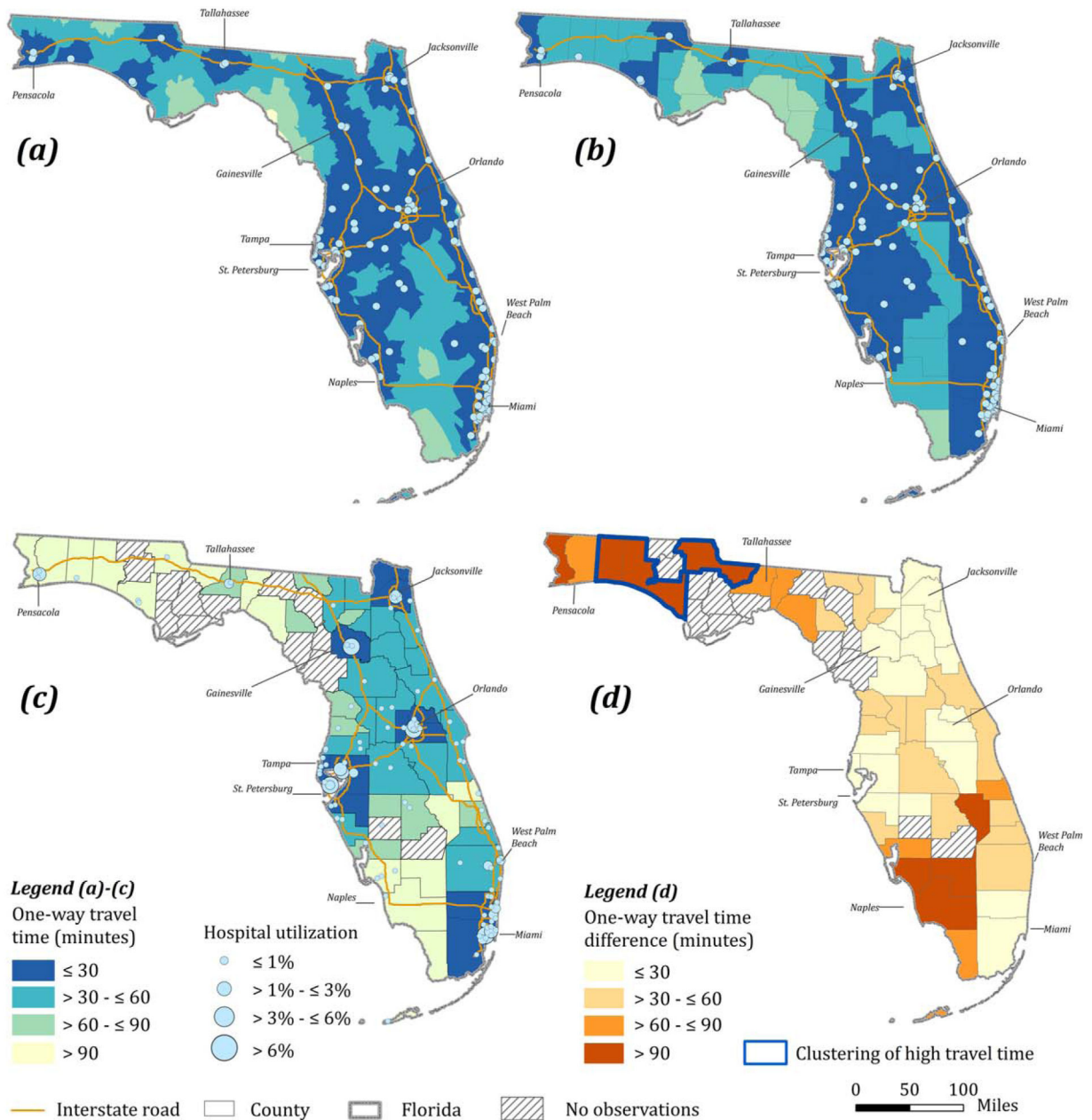
Figure 2. Illustration of the one-way network rule: travel route between two points using the customized road network in ArcGIS (a) and in GoogleMaps™ (b). c: Illustrates the three different travel impedances (i.e., Euclidean, shortest and fastest paths).



Sources: Agency for Health Care Administration, 1998 - 2008; Florida Birth Defects Registry, 1998 - 2007; U.S. Census Bureau, 2000 (www.census.gov); Florida Department of Transportation, 2007.

Figure 3.

Infants with spina bifida born in Florida 1998 to 2007 and whose mothers' residential address at delivery were successfully geocoded. **a:** Shows the spatial distribution of these infants. **b:** Indicates the locations of hospitals used at least once by these infants within their first year of life, and **(c)** shows travel patterns for these hospitalizations. To preserve confidentiality, the coordinates of the maternal residential address at delivery were geomasked. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]



Sources: Agency for Health Care Administration, 1998 - 2008; Florida Birth Defects Registry, 1998 - 2007; U.S. Census Bureau, 2000 (www.census.gov); Florida Department of Transportation, 2007.

Figure 4.

a: Theoretical one-way travel time to hospitals used by infants with spina bifida without anencephaly born in Florida, 1998 to 2007. Aggregation of one-way travel time (a) at the county level in (b) is based on the predominant drive time category (≤ 30 min, > 30 to ≤ 60 min, > 60 to ≤ 90 min or > 90 min). **c:** Represents the estimated average one-way travel time for hospitalizations, averaged per infant per hospitalization and aggregated at the county level. **d:** Summarizes the difference in one-way travel time (theoretical (fig. a) minus estimated average travel time (fig. c)) for those hospitalizations. Counties forming a significant local cluster of higher one-way travel time are outlined in blue (the local Moran's

I “LISA” statistic). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

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Table 1

Average One-Way Travel Time in Minutes from Infants' Maternal Residential Address at Delivery to Hospitalizations Initiated during the First Year of Life for Infants with Spina Bifida Born in Florida, 1998 to 2007 (Results are per Hospitalization per Infant)

Average travel time	N	Percentage
30 min	345	56.4
> 30 min and 60 min	130	21.2
> 60 min and 90 min	59	9.6
> 90 min	78	12.8

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Table 2
 Geographical Differences and Descriptive Statistics for the Estimated One-Way Travel Times in Minutes to Hospitalizations Initiated during the First Year of Life for Infants with Spina Bifida Born in Florida, 1998 to 2007

Geographic regions	N	Mean	Median	Minimum	Maximum
Non-urbanized area	87	68.1	46.6	7.21	494.1
Urban cluster	45	73.9	55.5	6.24	238.68
Urbanized area	480	38.3	22.2	2.43	437.63

Table 3

Spatial Autocorrelation Test (Moran's I) Results for Estimated Average One-Way Travel Time to Hospitalizations Initiated during the First Year of Life for Infants with Spina Bifida Born in Florida, 1998 to 2007

	Moran's index	z score	p value
County level			
Average network time	0.4	4.6	< 0.01
Average network distance	0.4	4.4	< 0.01
Regional level			
Average network time	-0.2	-0.2	0.9
Average network distance	-0.2	-0.1	0.9

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