

## Use of GIS Mapping as a Public Health Tool—From Cholera to Cancer

George J. Musa<sup>1</sup>, Po-Huang Chiang<sup>2</sup>, Tyler Sylk<sup>1</sup>, Rachel Bavley<sup>1</sup>, William Keating<sup>1,3</sup>,  
Bereketab Lakew<sup>1</sup>, Hui-Chen Tsou<sup>2</sup> and Christina W. Hoven<sup>1</sup>

<sup>1</sup>Child Psychiatric Epidemiology Group, Columbia University, New York State Psychiatric Group; <sup>2</sup>National Health Research Institutes, Taiwan, Republic of China (ROC). <sup>3</sup>Department of Geography, Hunter College, City University of New York, NYC, USA.

**ABSTRACT:** The field of medical geographic information systems (Medical GIS) has become extremely useful in understanding the bigger picture of public health. The discipline holds a substantial capacity to understand not only differences, but also similarities in population health all over the world. The main goal of marrying the disciplines of medical geography, public health and informatics is to understand how countless health issues impact populations, and the trends by which these populations are affected. From the 1990s to today, this practical approach has become a valued and progressive system in analyzing medical and epidemiological phenomena ranging from cholera to cancer. The instruments supporting this field include geographic information systems (GIS), disease surveillance, big data, and analytical approaches like the Geographical Analysis Machine (GAM), Dynamic Continuous Area Space Time Analysis (DYCAST), cellular automata, agent-based modeling, spatial statistics and self-organizing maps. The positive effects on disease mapping have proven to be tremendous as these instruments continue to have a great impact on the mission to improve worldwide health care. While traditional uses of GIS in public health are static and lacking real-time components, implementing a space-time animation in these instruments will be monumental as technology and data continue to grow.

**KEYWORDS:** GIS, Geographic Information Systems, Medical Geography, Epidemiology, Public Health, Spatial Epidemiology, Mapping

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**CORRESPONDENCE:** [chiangp@nhri.org.tw](mailto:chiangp@nhri.org.tw)

### Introduction

New diseases and epidemics spread through the world's population every year. The discipline of medical geographic information systems (GIS) provides a strong framework for our increasing ability to monitor these diseases and identify their causes. The field of medical geography has a much longer history than most are aware of, dating back to the first known doctor, Hippocrates, and progressing through the 1900s until today. The early history leads us to the examination of contemporary examples of GIS, influences on public health, space-time mapping components, and the future of this discipline supported by Big Data. The evolution of medical GIS from early disease maps to digital maps is a journey long in the making, and continues to evolve. These maps have enabled us to gain insight about diseases ranging from cholera to cancer, all while increasing the knowledge of worldwide health issues.

As modern technology continues to thrive, medical GIS will remain a lasting approach for understanding populations and the world we live in.

### A Brief History

Medical GIS has its foundation in medical geography, which, can be found in the literature of several ancient civilizations, including China, Greece, and India, with perhaps the earliest coming from the work of the first physician, Hippocrates in the 5th Century BCE, who was among the first to observe the relationships between human health and the environment. The term medical geography has its origins among French physicians in the 18th century<sup>1</sup> with the advent of modern thematic mapping, and the first disease map created by German physician Leonhard Ludwig Finke in 1792,<sup>2</sup> which became an important tool for understanding the incidence and spread of



infectious diseases, as well as identifying associations between disease and spatially-distributed environmental conditions.

Many early examples of medical cartography focused on the English cholera epidemic, which began in 1831 and spanned several decades. Dr. Robert Baker mapped the cholera incidence in Leeds, England during the first wave of the epidemic and used the map to identify higher incidence rates among the more densely populated parts of the city and among areas that lacked proper sanitation.<sup>3</sup> In 1848, Dr. Thomas Shapter published a dot density map of 1,100 deaths from cholera in Exeter that occurred between 1832 and 1834, using different symbols for deaths occurring in different years.<sup>3</sup> German geographer Augustus Petermann created a series of Cholera maps of the British Isles in 1952, used to show the geographical extent of the 1931–33 epidemic and discover environmental or local conditions, which may affect the diffusion of disease.<sup>3</sup>

Perhaps the most famous exemplar of early medical geography was Dr. John Snow, considered to be the father of modern epidemiology, who demonstrated the water-borne origin of cholera by plotting cholera-related deaths in London during the most severe 1854 epidemic on maps. In addition to disease cases, he also plotted the city's water pumps, and drew concentric circles to determine that the area with the highest concentration of cases were within close proximity to the Broad Street pump. Removing the pump led to the almost immediate end to new cases in the area, proving that drinking water from this pump was an important causative agent in the epidemic.<sup>3</sup> These early mapping techniques proved extremely useful for elucidating the geospatial correlates of disease incidence and spread. The main obstacle for early physicians/medical geographers was limited technology and acquisition of data. Maps had to be drawn by hand, making them difficult to reproduce, and since physicians were the ones with medical data, it was they, not geographers, who first mapped disease patterns. That, however, changed at the turn of the century.

Medical geography underwent a transition in the late 19th and early 20th centuries from a largely descriptive science to an analytical science, accompanied by an explosion of new publications and academic societies devoted to it.<sup>1,4</sup> This progression was influenced by a number of contributing factors, including the large-scale migration of people into new areas, exposure to previously unknown diseases, and the rise of medical schools and journals that could provide more immediate information of diseases.<sup>4</sup> Increasingly sophisticated medical research and new scientific techniques also proved vital to the proliferation of the field, advancements that were made possible by increased funding from governments and private institutions, and innovations in map making, such as the introduction of improved mechanical equipment and the wider availability of base maps on which to plot statistical information.<sup>4</sup>

Contemporary medical geography as a discipline was heavily influenced by several important foundational thinkers in the mid 20th century, including Jacques M. May. May emphasized that disease was the product of interaction

between pathological factors (including causative agents, vectors, immediate hosts, reservoirs, and man), and geographical factors (at the physical, biological, and social level).<sup>5</sup> He also laid out a research agenda for the field, which included the following objectives: "(1) A census of what is known and a discussion of every problem suggested by the tabulation. (2) The study of a disease, taken as an example of the endemic-epidemic type, against its environment. (3) The study of a region with reference to the disease it produces. This should include sample studies of population, in order to work out a reliable statistical method for the computation of the prevalence of diseases".<sup>5,p.40</sup>

## Medical GIS

Rapid advancements in computer technology during the latter half of the 20th Century brought about an enormous transformation of medical geography and made modern medical GIS possible. By the late 1960s, several computer-mapping programs began to revolutionize the discipline, catalyzing the development of modern automated mapping procedures, which allowed for information to be more readily and efficiently updated. Maps could now be generated much faster and with greater precision than before, and disease diffusion could more easily be mapped and analyzed. "An approach through knowledge of population movement patterns allows cultural interactions with the environment to be studied without preconceived compartmentalization inappropriately derived from other places or cultures".<sup>6,p.393</sup> Through these maps, an objective way to look at geographical and medical facts became possible.

The early 1970s brought about a new wave of analytical approaches, making hypothesis testing more important to the field. Increasingly, researchers were interested in not only describing diseases and their spread, but also how human behavior and interactions with the environment affect one another. With the rise of computerized statistical packages, more complex models could be used to analyze spatial information.

By the middle of the 1980's, computer mapping technology flourished, allowing more non-spatial data, called "attribute data", to be linked to spatial point data in digital maps, leading to the birth of the modern desktop-based GIS. In addition to mapping point densities, one could now use GIS to test statistically whether these points tended to cluster in certain locations, and whether disease patterns were significantly associated with other aspects of human interactions. While such statistical associations cannot determine causation, they are extremely useful for increasing our understanding of disease patterns.

A GIS can be defined as a computer system with the capacity to capture, store, analyze, and display geographically-referenced information. In other words, it is an informatics for storing and managing data that has been identified according to location. GIS have been used in a wide variety of fields, including the natural, social, engineering, and particularly



the medical sciences because of their ability to incorporate physical, biological, cultural, demographic, or economic information.

One of the first notable medical GIS software is referred to as the Geographic Analysis Machine (GAM), developed in 1987 by Openshaw and his colleagues and used to analyze locations of clusters of Leukemia in 1983. This system “contained 4 major components: (1) a spatial hypothesis generator; (2) a significance assessment procedure; (3) a GIS to handle spatial data retrieval requests; and (4) a geographical display and post map processing system”.<sup>8,p.99</sup> In the paper entitled *Searching for Leukemia Clusters Using a Geographical Analysis Machine*,<sup>8</sup> an analysis was performed to test whether living in close proximity to a nuclear facility posed a higher risk of pediatric cancer. With the use of the GAM, Openshaw was able to demonstrate clustering effects of Leukemia and other cancers. He also found that several clusters identified in previous studies were not statistically significant in their model. Although GAM proved to be a very powerful instrument, Openshaw warned that using GAM alone would not be enough to identify the causes of leukemia and that more “non-geographic micro studies to identify causal agents involved” needed to be done.<sup>7,p.105</sup> Despite these limitations, the GAM provided an early example of how powerful new geographic computing technologies could be when applied to real-world public health challenges.

### Current Traditional Use of GIS in Public Health

GIS has brought together research methods and analytic techniques from both medical geography and spatial epidemiology, and is currently being used in a wide variety of health science applications. The past decade has seen a sharp rise in the number of epidemiological studies employing GIS, particularly in the areas of health disparities, resources availability, and health-related behaviors, as well as continued use in more foundational fields such as cancer and environmental epidemiology.<sup>9</sup>

Epidemiologists use GIS to assess proximity, aggregation, and clustering, as well as to perform spatial smoothing, interpolation and spatial regression.<sup>9</sup> The most common application of GIS in these fields remains the identification of disease clusters, which refer to nonrandom spatial distributions of disease cases, incidence, or prevalence. Multiple analytical and statistical techniques have been devised to identify multiple forms of clustering. These include (1) global clustering, in which no cluster areas are pre-specified and the presence of clusters is derived empirically, (2) local clustering, in which specific small-scale clusters are evaluated statistically, and (3) focal clustering, which assesses clustering around a predetermined point such as an environmental hazard.<sup>9</sup>

GIS has also been used extensively in epidemiology for disease surveillance and intervention monitoring.<sup>10</sup> By mapping disease cases in geographic space, local and national governments can easily identify the distribution and spread

of disease across geographic regions, optimize planning of intervention locations, and monitor their effectiveness. Such applications of GIS, in combination with other technologies such as global positioning systems (GPS) and remote sensing, have been successfully employed in the monitoring and control of onchocerciasis in Guatemala, trypanosomiasis in Africa, and malaria in Israel and Mexico.<sup>10</sup>

### GIS and Health Services

In addition to traditional epidemiological applications, medical geographers have the ability to assess the spatial distribution and accessibility of health services using GIS.<sup>11-14</sup> Health care is an important subject for medical geography, as modern political pressures and growing disparities in health services has compelled many administrations to reevaluate health care systems to accommodate current health care needs. GIS can be used in a variety of ways to visually display health service utilization as well as take into account the many factors related to locational constraints, which may limit an individual from acquiring proper health care. Location-allocation models are used to identify how gaps in health services among specific communities can be reduced. Existing health services mapped along with road networks are used to identify and facilitate patient travel.<sup>15</sup> Access to health care is largely determined by cultural, social and economic barriers in addition to geography;<sup>16</sup> simply adding more services does not automatically increase population access. However, using these techniques offers great promise for improving the distribution of health resources and identifying service gaps.

Valuable information such as population distribution,<sup>17</sup> income and poverty levels, can be visually displayed to determine the best possible placement of new services, as well as to identify specific regions that are underserved.<sup>13</sup> These factors can be calculated and modeled to predict potential health care accessibility issues and future service needs. One such example of this is the gravity model, which not only takes into account Euclidean distance between individual residences and health care providers, but also factors in price, quality of service, accommodations, and cultural appropriateness in order to determine which particular facilities offer more ‘attractive’ health care services to specific subsets of the population; and thus, identifies patterns of accessibility and provides insight into population composition and their specific needs.<sup>13</sup>

Beyond analyzing the geographical locations of health service facilities, GIS allows policymakers to better assess potential risk factors and prevent disease.<sup>13</sup> A recent project concerning risk evaluations and health planning against influenza in Taiwan demonstrated the value of GIS in public health planning and potential disease prevention. Combining population distribution, elevation, land cover, location and capacity of existing health services, researchers were able to calculate the population covered by existing services within Miaoli County.<sup>18</sup> Raster and vector data were then used to



simulate a pandemic flu outbreak and to determine which areas within the county required additional facilities.<sup>18</sup>

### Current Limitations of GIS

While GIS has become increasingly popular among both medical geographers and epidemiologists, there is also a growing concern over the capabilities of this technology and its application for medical research. Some have argued that current commercial off-the-shelf (COTS) GIS software such as ArcGIS and MapInfo do not provide the necessary tools that are appropriate to conduct thorough epidemiological research, and that few spatial studies have soundly demonstrated any unique or substantial contributions of GIS to the field of epidemiology.<sup>19</sup> It has been argued that while GIS is a powerful tool for many descriptive techniques, such as cartography, location-allocation, characterization of populations, spatial statistics and spatial models, these applications do not offer any ground breaking insights into the determinants of population health and disease. GIS and associated spatial analytical techniques have thus far been limited by their lack of a temporal component, which has led to most studies presenting only a static snapshot of disease distribution based on cross-sectional data, rather than representing the dynamic progression of disease through time and space. The lack of complex statistical capabilities of current GIS software programs, has led most health researchers to use GIS for only limited functions, while using outside programs like SPSS or SAS to perform the actual statistical analyses.<sup>20</sup> Furthermore, most spatial analysis techniques were developed for non-health fields, and are therefore not well-suited to the types of count and aggregate data most accessible to health researchers.<sup>20</sup> New analytic tools and accompanying technological innovations are clearly necessary to move the field forward. The remainder of this paper will address emerging developments in the field that seek to overcome these limitations, and discuss where we believe the field is headed.

### Space-Time Representation

Space-time representation is one of the current frontiers in the evolution of GIS, and is considered by many to be an essential component of the spatial analysis of disease patterns. Kistemann, Dangendorf, and Schweikart<sup>21</sup> emphasize the importance of integrating spatial and temporal elements in their definition of geographical epidemiology as “the collection and analysis of spatial patterns of disease appearance and disease-specific deaths, taking into consideration the social, economic, ecological and demographic prerequisites of space and time”.<sup>22,p.659–660</sup> Space-time representation is the illustration of the distribution of events over a specific period of time and location. Dr. Peuquet, Professor of Geography and Associate Director of GeoVISTA Center at Pennsylvania State University, described the importance of adding a time component to geographical data: “[I]nclusion of the temporal element in the data is required, in everyday life, as

well as in scientific study, in order to derive cause-and-effect relationships and ultimately an understanding of nature and structure of various elements in the world around us”.<sup>22,p.659–660</sup>

Much of the current focus on space-time representation has revolved around animation, which essentially involves combining a series of cross-sectional maps taken at different time points to display how such snapshots change over time. Animation can be integrated with GIS, and has proven to be extremely effective in visualizing the spread or recoiling of disease over space and time. Epidemiological studies often involve mapping the diffusion of various diseases over time in a given space, and the analysis of this geospatial diffusion has the potential to lead to greater opportunities for disease control and prevention. However, most animation techniques are merely descriptive, which severely limits their utility in analyzing spatial patterns in the spread of disease and relationships between environmental exposures and health outcomes.

One notable example of the innovative application of space-time representation to disease monitoring is the dynamic continuous-area space-time (DYCAST) system,<sup>23</sup> which was successfully used to monitor and predict the spread of West Nile virus in New York City. Daily data from the city’s surveillance of dead crows (a marker for the presence of West Nile virus) was geocoded by address where the bird was found and entered into an object-oriented GIS along with the date it was reported and other attribute information. A model of the association between the spatiotemporal distribution of dead crows and the location and timing of human West Nile Virus cases was developed and calibrated based on surveillance data from 2000. The DYCAST system then overlaid the map of New York city with a 1400-cell grid, and a moving window scanned the grid, calculating whether the number of dead crows found within a 1.5 mile radius of each cell’s centroid were statistically close in both space and time (where close in time was defined as with 21 days) based on the Knox statistical method. Using this model, researchers were able to prospectively identify high-risk areas for West Nile Virus at least 13 days before disease onset, predicting 5 out of the 7 human cases that occurred in 2001. DYCAST represented a significant improvement over previous models, which relied heavily on reports of dead crows and positive testing of West Nile infection, both of which are slow and unreliable, and illustrates the practical utility of space-time representation for public health applications.

The expanding pool of analytical techniques that allow for a greater integration of spatial and temporal data has been accompanied by rich new sources of geotemporal data. As portable GPS devices become more common and are increasingly integrated with popular social media platforms, unprecedented levels and types of data may become available for analysis.<sup>9</sup> Technological innovations and the new kinds of data they produce will require innovative analytical techniques that will move the field forward and open up previously impossible lines of geospatial research and increasingly diverse applications of GIS. While both the logistical and ethical obstacles



to such work are substantial, this is an area with tremendous potential that will likely play a large role in the future of time-space representation.

Kwan and associates, at Ohio State University, are pioneers in incorporating “time” as a dimension in GIS when analyzing human travel patterns and accessibility.<sup>24–28</sup> When analyzing travel patterns, the researchers overlay maps within the GIS and use lines to traverse and thus visualize the space-time paths.<sup>24,25</sup> Cumulative space-time activities and accessibility are mapped in 3-dimensional graphs illustrating accessibility surfaces.<sup>27,28</sup> These same approaches used to analyze accessibility and travel patterns can easily be applied to health to observe space-time spread of disease and to enhance location-allocation models of treatment facilities.

### Big Data

One of the current advancements in the fields of Medical GIS is coming from our increasing ability to collect and analyze mass amounts of information, a phenomenon known as Big Data. “Big Data refers to datasets whose size is beyond the ability of typical database software tools to capture, store, manage, and analyze”.<sup>29,p.11</sup> Two major influential factors contributing to this phenomenon are the growing sizes of common datasets in the industry and the increasing availability of software tools capable of processing them. In many sectors, Big Data will range “from few dozen terabytes to multiple petabytes (thousands of terabytes)”.<sup>29,p.11</sup> Since GIS incorporates spatial analysis with available data, utilizing large data sets could eventually provide us with up-to-date information on medical and social trends. Social networking is only one of the sources leaking large amounts of data into the hands of medical geographers.

In addition to population health, GIS is extending its focus into modern social technologies in order to take advantage of large datasets. “GIS provide a digital lens for exploring the dynamic connections between people, their health and well being, and changing physical and social environments.”<sup>30,p.3</sup> It is reported that 340 millions tweets are sent per day (nearly 4,000 tweets per second) and more than 901 million Facebook status updates.<sup>31</sup> Although only a fraction of these online-social media activities are geo-located, by mining health-related geo-located tweets, space-time analyses of these tweets can glean spatial-temporal patterns of disease transmission.

Big Data can also help with determining urban mobility in the case of an emergency evacuation.<sup>31</sup> Zia et al (2013)<sup>32</sup> proposed scenarios using GIS tools that would enable city planners to take these situations into consideration. They found that individual differences would be a challenge in determining actual behavior and reactions in the cases of emergencies.<sup>32</sup>

Health institutions have the opportunity to utilize medical GIS using their large sets of medical records and discharge information. This information can be used to increase

the accessibility of health services in order to increase the availability of services to populations in need, as well as to improve the internal recognition of illness patterns. Not only are medical geographers responding to the compatibility of digitizing large data sets, but to the “Obama administration’s \$14.6 billion program launched in 2009 to encourage adoption of electronic medical records”. McClafferty (2003)<sup>15</sup> explains that the combination of GIS with data about medical trends and needs can help to improve the accessibility and utilization of health care.

### Conclusions

Medical GIS is a link between biomedical and social sciences. The demand for GIS in the health field parallels the advancements in disease control. It is an invaluable approach, which identifies and maps medically vulnerable populations, health outcomes, risk factors and the relationships between them. The capacity of GIS to link disease information with environmental and spatial data makes it an asset in the progression of worldwide healthcare. Additionally, health organizations can now visualize, analyze, interpret and display multifaceted geo-location data through the use of GIS tools, mapping applications and Big Data. These new tools have unleashed new modeling techniques previously thought impossible. Continuing innovations in GIS and Big Data make this an exciting time for medical GIS, and it will be interesting to witness how new technologies, analytical techniques, and data sources will shape the future of the discipline.

### Author Contributions

Conceived the concept: PHC, GJM. Wrote the first draft of the manuscript: GJM, PHC. Contributed to the writing of the manuscript: PHC, GJM, TS, RB, WK, BL, HCT, CWH. Agree with manuscript results and conclusions: PHC, GJM, TS, RB, WK, BL, HCT, CWH. Jointly developed the structure and arguments for the paper: PHC, GJM, TS, RB. Made critical revisions and approved final version: PHC, GJM, TS, RB, WK, BL, HCT, CWH. All authors reviewed and approved of the final manuscript.

### DISCLOSURES AND ETHICS

As a requirement of publication the authors have provided signed confirmation of their compliance with ethical and legal obligations including but not limited to compliance with ICMJE authorship and competing interests guidelines, that the article is neither under consideration for publication nor published elsewhere, of their compliance with legal and ethical guidelines concerning human and animal research participants (if applicable), and that permission has been obtained for reproduction of any copyrighted material. This article was subject to blind, independent, expert peer review. The reviewers reported no competing interests. Provenance: the authors were invited to submit this paper.

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