

Geographic Information Systems in Spatial Epidemiology: Unveiling New Horizons in Dental Public Health

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INTRODUCTION

The importance of environment in health and sickness has been identified as early as the times of Hippocrates, who, in his book “Airs, waters and places,” mentioned that “a person’s health is influenced by the air he breathes, the water he drinks, and the environment in which he lives.”^[1]

Since then, health professionals have, time and again, used geographic maps to point and analyze the associations between environment and diseases. In the modern era, evidence of early use of maps for public health analysis was showed by Dr John Snow, who

mapped the cholera cases in London in 1854. These maps are called cartograms or topographs. But, these could only provide information on location.^[1,2]

In the recent times and notably in the last three decades, this field has undergone a transition from descriptive science to analytical science. This has been possible mostly by virtue of improved technical equipment

ABSTRACT **Objectives:** Research on the role of environment and place in various aspects of dental public health using geographic information systems (GIS) is escalating rapidly. Yet, the understanding of GIS and the analytical tools that it offers are still vaguely understood. This narrative review therefore draws from the utilization of GIS in the dental public health research. **Materials and Methods:** Electronic databases such as Google Scholar, PUBMED, and Scopus were searched using terms “spatial epidemiology,” “GIS,” “geographic information systems,” “health geography,” “environment public health tracking,” “spatial distribution,” “disease mapping,” “geographic correlation studies,” “cartography,” “big data,” and “disease clustering” through December 2019. **Results:** This review builds upon the prospects of GIS application in various aspects of dental public health. Studies were classified as: (1) GIS for mapping of disease, population at risk, and risk factors; (2) GIS in geographic correlation studies; (3) GIS for gauging healthcare accessibility and spatial distribution of healthcare providers. We also identified the commonly used GIS analytical techniques in oral epidemiology. **Conclusions:** We anticipate that this review will spur advancement in the utilization of spatial analytical techniques and GIS in the dental public health research.

KEYWORDS: Environmental health, geographic information systems, medical topography, public health, spatial analysis

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and increasing arrays of online base maps, on which the statistical information can be plotted.^[3] This new discipline, “Spatial Epidemiology,” can be described as being “concerned with describing, quantifying, and explaining geographical variations in disease, especially with respect to variations in environmental exposures at the small-area scale.”^[4,5] It helps in answering some seemingly simple geographical questions like: What is the distribution of a condition in a certain geographical area? Are there any patterns found and trends in disease incidence that could help predict incidence in the future? What is the accessibility of a certain area to the nearest health center? Thus, the art and science required to answer these geographical questions forms spatial epidemiology, and the technology required to resolve these questions is called geographical information system (GIS).

Applications in GIS can be broadly classified into four main domains^[5-7] [Figure 1]:

1. *Measurement*: gauging the distribution of communicable and non-communicable diseases in an area and the environment’s effect on them. It incorporates not only medical, but also demographic and political data.
2. *Mapping*: developing maps that portray characteristics and help in the spatial understanding of a population’s health. Also gauges the healthcare access and spatial distribution of healthcare providers.
3. *Monitoring*: monitor changes in health and diseases in space and time. It can conduct environment public health tracking (EPHT) for disease and exposures: so that public health actions can be planned, implemented, and monitored to prevent and control environment-related diseases.
4. *Modeling*: to model alternatives of actions and process operations based on the risk prediction of diseases.

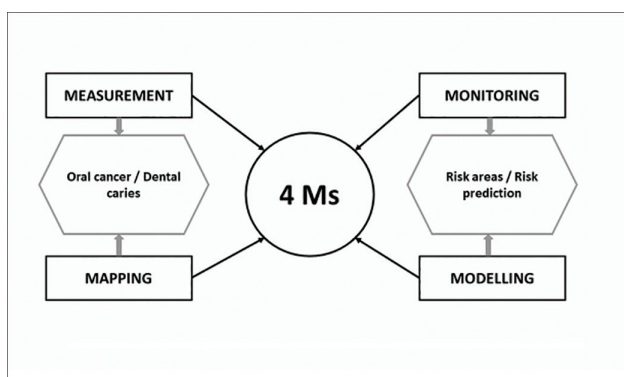


Figure 1: Schematic representation of four Ms: Measurement, mapping, monitoring, and modeling

The role of environment and place in various aspects of dental public health is now being affirmed by researchers using GIS. Association of dental caries, oropharyngeal cancers, oral and maxillofacial injuries, and periodontal diseases with various environmental factors such as access to public and private healthcare centers, school dental clinics, dentist shortages, areas in need of dental facilities, intervention effects on oral health, and individual and contextual level pathways to the oral health outcomes is being explored and analyzed.^[8-22]

This article builds upon the spatial epidemiology and prospects of GIS application in the various aspects of dental public health. It also draws from the utilization of GIS in the studies in dental public health. The current article also focusses on the methodological advances in GIS.

MATERIALS AND METHODS

This narrative review elucidates the recent literature on GIS in spatial epidemiology of oral health. Electronic databases such as Google Scholar, PUBMED, and Scopus were searched using terms “spatial epidemiology,” “GIS,” “geographic information systems,” “health geography,” “environment public health tracking,” “spatial distribution,” “disease mapping,” “geographic correlation studies,” “cartography,” “big data,” and “disease clustering” through December 2019. The authors also hand searched for references from the retrieved literatures. They excluded articles not published in English language, case reports, and editorials but read them to identify any relevant literatures.

The review is organized according to major premises in spatial epidemiology. The section overview presents some commonly used GIS terminologies and key instruments supporting spatial epidemiology, as this paper is structured to provide a framework for readers who may have little familiarity with GIS. The first section describes some commonly used terminologies. The second section focusses on the most significant instrument supporting spatial epidemiology, the GIS. The third section covers the studies that are conducted on different aspects of dental public health and analysis by virtue of GIS.

TERMINOLOGIES USED IN SPATIAL EPIDEMIOLOGY

- a. *The concept of place*: It implies the “place” where an individual lives or works. A neighborhood is defined as the geographic area relevant to the specific health outcome being studied.^[3]

- b. *Data for spatial analysis*: Data here implies spatial data or geo-referenced data, to which the geographic coordinates are attached. This is done by Geocoding, a process in which the locational information [address, health center location] can be transformed into geographic coordinates with the help of global positioning systems (GPS). These spatial data can be linked to the “attribute data” or the non-spatial data, thus forming digital maps and spatial analysis.^[3]
- c. *Point and area data*: Data used in the spatial epidemiology can be point and area data. When every item of health data may be connected.
- d. *Data linkages*: Data from various databases can be linked across spatial units using geocodes. Even in aspatial studies, data from vital records can be linked with socioeconomic data using state-level geocodes.

GEOGRAPHIC INFORMATION SYSTEMS (GIS)

GIS can be defined as “a computer software for data capturing, thematic mapping, updating, retrieving, structured querying, and analyzing the distribution and differentiation of various phenomena, including communicable and non-communicable diseases across the world with reference to various periods.” In simple words, GIS is a combination of map and database, in which the spatial and temporal data can be integrated and analyzed. GIS is a generic term denoting the use of computers to create and depict digital representations of the Earth’s surface.^[23,24] It can identify the areas where people might be exposed to biological and environmental agents and can analyze the spatial and temporal patterns in disease/health outcomes.^[24-26]

Scope of GIS is as follows:

- *Mapping*: digitization of cartography,
- *Analysis*: adding spatial dimension to biostatistics.

GIS has the inherent ability of mapping with signs and symbols, lines and polylines, shades and patterns. It has symbols and colors for thematic or customized mapping. Measurements that are done using GIS are distances: as-the-crow-flies or traversed paths, surface areas, altitudes, buffer zones, and perimeters.^[27-29]

Some GIS analytical techniques commonly used in oral epidemiology are^[8-22]:

1. *Density mapping using kernel density and point density*: Kernel density calculates the density of features in a neighborhood around those features per unit area in a raster format. It can be used with both the point and line data. It is used in finding

density of cases, vectors, risk factors, etc. Point density uses point features and amalgamates the points in neighborhood to create a density map.

2. *Overlay analysis*: The characteristics of several datasets are combined into one map and are generally used to find the locations that are susceptible to a particular risk.
3. *Exploratory data analysis*: The analysis helps to gain a deeper understanding of the investigating phenomenon.
4. *Nearest neighbor analysis*: It finds the closest subset of input samples to a query point and applies weights to them based on proportionate areas.
5. *Interpolation*: It is filling the gaps with predicted, assumed, or modeled values based on the available data and done by IDW and Kriging. The IDW (Inverse Distance Weighted) tool is interpolated by estimating the cell values by averaging sample data points values in the neighborhood of each processing cell. Kriging gives the best linear unbiased prediction and works by computing weighted average of known values.
6. *Spatial autocorrelation*: done by
 - Getis and Ord’s Gi statistic: A positive value of Gi denotes hotspot and negative value denotes cold spot.
 - Anselin’s LISA (local indicators of spatial autocorrelation) or a local version of Moran’s I: LISA close to zero means no statistical autocorrelation among neighboring areas. High LISA values indicate hotspots, negative LISA indicates clustering of dissimilar values.
 - Moran’s I: It is similar to Pearson’s correlation coefficient. It is approximately normally distributed and has an expected value of $-1/[N-1]$ where N represents the areas included. Moran’s index has values ranging from 1.0 to + 1.0 and measures how close the objects are in comparison with other close objects.
 - Geary’s C: It considers similarity between pairs of regions. Values range from 0 to 2.
7. *Spatial clustering*: Objects are grouped based on their spatial similarity into meaningful clusters. Various methods used here are Besag and Newell’s R method, Amoeba method for clusters that are not of well-defined shape, Ripley’s K-function: Ideal for comparing clustering of cases and controls or Cuzick and Edward’s k -nearest neighbor test.

Clusters with highest Gi values are designated as important clusters and their statistical significance is tested using Monte Carlo randomization methods.

Space time clustering is done for the understanding of the role of time along with space, where space–time paths are created.

8. *Pattern recognition and spatial prediction*: The geostatistical analysis of remote sensing and environmental variables and the creation of spatial models provide reliable results. The algorithms created can predict the risk of disease transmission with reference to space and time.

GIS APPLICATIONS IN DENTAL PUBLIC HEALTH CAN BE UNDERSTOOD IN THE FOLLOWING ASPECTS^[4,30]

GIS for mapping of disease, population at risk, and risk factors

Maps help us to visualize complicated geographic information [Table 1]. They help in identifying the patterns in data that are otherwise abstract to the reader. Disease mapping is used chiefly for descriptive purposes, to form etiological hypotheses and for surveillance of possible high-risk areas so as to take preventive actions.

Risk of caries in children and adolescents was conducted among children by Ulf Strömberg *et al.*^[8] Geo-coding of each child was done corresponding to his/her residence parish. A parish-specific relative risk (RR) was estimated as observed-to-expected ratio. The authors could create smoothed caries risk geo-maps, as well as corresponding statistical certainty geo-maps.^[8]

In another study by Fonseca *et al.*,^[9] we calculate the crude rate and applied Bayesian methods for death rates due to oral and oropharyngeal cancers, which were mapped.^[9]

Spatial and spatio-temporal distribution of oral and maxillofacial injuries caused by urban violence was done by mapping using GIS by de Macedo Bernardino *et al.*^[19] The finite mixture model was used to evaluate the longitudinal patterns of change observed in each geographic area. The authors used Getis–Ord indicator (G_i^*) to identify significant hot and cold spatial clusters that allowed them to assess spatial autocorrelation of events.^[10]

Geographic correlation studies

Geographic correlation research helps in assessing the variations in exposure of different population groups to the environmental variables (that may be measured in the air, water, or soil), socioeconomic and demographic measures (like ethnicity, income, etc.), or lifestyle factors (like smoking, diet patterns,

etc.) with respect to the health outcomes measured on a geographic scale.^[31]

In a study that examined the probable risk caused by residence-associated factors for caries prevalence such as dentist density, fluoride level of drinking water, and urban–rural location, the maps were prepared to illustrate the categorized caries levels. The authors performed multilevel analysis using generalized linear mixed models and a logit link function.^[31]

Antunes *et al.*^[12] conducted a study to examine the association between dental decay and treatment needs in 5–12-year olds in São Paulo by performing spatial data analysis. Spatial distribution was analyzed by construction of the proximity matrix. Spatial autocorrelation of the variables of interest was evaluated using the “I” indicator of Moran. Empirical Bayes estimation was used to calculate the risk of tooth decay. *K*-means cluster analysis method was utilized for the classification of risk of caries. Gini coefficient is used to gauge the concentration of variables, and here, the income inequalities.^[12]

Pereira *et al.*^[13] investigated the distribution of dental caries and its association with regions of social deprivation at the individual and contextual levels. They measured the spatial distribution of dental caries to allocate the resources. In this study, though multi-level analysis did not show statistical association, spatial analysis was able to detect the association. At the individual level, social and economic variables were associated with high dental caries, but not at the territorial level.^[19]

In a study done by Moi *et al.*,^[14] spatial autocorrelation of various epidemiological aspects was done with the mortality rates due to oral cancer using “I” indicator of Moran. It analyzed various factors associated with the spatial clusters of oral cancer mortality.

GIS techniques for gauging healthcare accessibility and spatial distribution of healthcare providers

Measuring the geographic disparities was traditionally done by calculating the physician-to-population ratios that were largely inaccurate. Whereas, now, the understanding of health needs and delivery of health care have substantially been changed due to GIS. Digital data sharing protocols connected to a computer through internet have been developed, making it very easy to collect and process the data. Health service utilization data is now available in the digital form as medical records or hospital discharge data sets, allowing to gauge the health service utilization patterns and access to health care.^[32-34]

Access describes “the people’s ability to use health services when and where they are needed.” Access to health care is different from the geographic accessibility, in that the former encompasses both spatial components (availability and accessibility) and aspatial components (acceptability and affordability). The latter, that is, the geographic accessibility, comprises only the spatial components. There are various techniques to measure this accessibility to healthcare facilities. It requires configuration of healthcare facilities, distribution of population, and the transportation infrastructure.

Measuring the distance can be area-based or distance-based. Area-based measures work with predefined area units, mostly the political units that do not take into account the cross-area travel. This is one of the important disadvantages of area-based studies. Nevertheless, many studies use this measure for measuring access. In a study done by Ranasinghe *et al.*^[18] to measure the distribution of school dental clinics in relation to the child population distribution and socioeconomic status, a concentric buffer distance of 5 km was considered as the reasonable estimate of travel distance. The authors could identify noticeable gaps in the distribution. Perere *et al.*^[19] conducted a study to gauge the location of public dental clinics, where an empirical 2 km buffer zones was applied and each area was identified with/without a centroid falling within the buffer.

Distance-based measures focus on the travel time or cost between the population and healthcare provider, avoiding many of the above problems. The most widely used distance-based measure is the straight-line or Euclidean distance that calculates vehicular travel time over a road network in GIS. Other measures include connectivity analysis, shortest path analysis, routing, service areas, location-allocation modeling and accessibility modeling, and so on.^[34] The traditional

distance measure (Euclidean) has now been replaced with more credible measures such as travel distance or time. In a study conducted by Delamater *et al.*,^[15] the conceptual and practical differences between raster and network data models were reviewed. Results showed that the raster-based method identified more area and people with limited accessibility.

Another method employed is kernel density estimation (KDE) to assess the availability of health care. KDE can estimate total health facilities and the number of health facility staff in a region to be compared with the number of people in a given population. Health facility can be represented as a dot on a map, and the geographic range of that facility’s influence, or its “service area,” is also taken into account. Maps produced from KDE use facility locations, staffing, capacity, and other attributes, as well as the population distribution in that region.^[34,35] Feng *et al.*^[16] conducted a study to describe variations in dental service utilization with respect to dental workforce availability. The authors performed spatial autocorrelation using “I” indicator of Moran and bivariate local indicators of spatial relation [bLISA]. While the first one measures the global spatial autocorrelation, the latter helps in locally identifying the spatial patterns. Geographically weighted regression was used to display spatially varying relationships of utilization with workforce availability.

Several studies have also calculated the practice-to-population ratios and then classify them as high, medium, and low levels to identify areas with low dentist-to-population ratio and areas where no dentists are available.^[17,20]

WHAT NEXT?

Spatial epidemiology has now substantially moved from “national disease mapping” to smaller provincial

Table 1: Dental public health research entailing various GIS functions and associated epidemiological applications

GIS functions	Application to dental public health
Identify spatial patterns	<ul style="list-style-type: none"> Spatial and spatio-temporal patterns of oral and maxillofacial injuries Spatial distribution of dental caries
Display spatial associations	<ul style="list-style-type: none"> Dental caries association with various factors Oral and oropharyngeal cancers associations
Analyze the spatial associations	<ul style="list-style-type: none"> Maps showing relationship between the prevalence of dental caries and associated factors among young adults Analysis of factors associated with deaths due to oral cancer
Measure accessibility to health facilities	<ul style="list-style-type: none"> Geospatial analysis of accessibility to school dental services using census and deprivation data Coverage of oral healthcare services provided to antenatal mothers Analysis of dental services distribution using buffer zones that delineate the service coverage areas or Euclidean/straight line distances to the health centers
Analyze the treatment needs	<ul style="list-style-type: none"> Identifying the differentials in dental needs using area-based measures

and local area mapping. It has now moved from just mapping of diseases to spatial prediction of diseases at a resolution of kilometers. The algorithms/models created can help in the spatial prediction of disease transmission risk.^[36,37]

In future, monitoring and further reduction of risk by locating the patient so as to reduce the mortality and disability can be envisaged. Path traced by patient (as daily routine) can be traced to identify probable indicators for cancers.

Possibility of new areas that we can think of, like finding an area without a dental care (geographic area without a dental clinic) where one can provide the service by means of camps, can be done using buffer analysis.

Early identification of cancer can be done by locating the patient's residence and relating to previous history and surroundings.

Space-time representation to disease monitoring done by the Dynamic Continuous-Area Space-Time (DYCAST) system is another prospect in the GIS evolution. It monitors the spread of infectious diseases and hence can predict its further diffusion.

CONCLUSIONS

Spatial epidemiology has developed to form an impending connection between social and biomedical sciences. GIS has now become an imperative tool, because of its instantaneous visual appeal as well as availability of the newer spatial analytical techniques. This narrative review has summarized the dental public health studies done using GIS and various techniques and applications of GIS that can be employed in future research.

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AUTHOR CONTRIBUTIONS

P. P. N. has contributed in conceptualization, definition of intellectual content, literature search, manuscript preparation, and final approval of the manuscript. J. B. P. has contributed in conceptualization, literature search, manuscript preparation, and final approval of the manuscript. N. S. has contributed in the definition of intellectual content, literature search, manuscript preparation, and final approval of the manuscript. K. S. S. and D. K. have contributed in the definition

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PATIENT DECLARATION OF CONSENT

Not applicable.

DATA AVAILABILITY STATEMENT

Not applicable.

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