NOT ALL MAPS ARE EQUAL: GIS AND SPATIAL ANALYSIS IN EPIDEMIOLOGY

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ABSTRACT

Recently, Geographical Information System (GIS) has emerged as an innovative and important component of many projects in public health and epidemiology. One of the most useful functions of GIS in epidemiology continues to be its utility in basic mapping. GIS may also involve more sophisticated spatial analysis of disease occurrence and contributing environmental factors. Depending on the quantity and quality of data and the methodology used in analysis, a given map may be either useful or misleading. Although visual analyses (mapped evidence) strengthened by exploratory analyses are mostly sufficient for epidemiologists, the formal testing of certain hypotheses or the estimation of relationships between measures of disease incidence and, for example, environmental covariates require quantitative modelling of disease distribution. It is a promising prospect that spatial statistics and GIS technology have slowly started to merge. However, whether GIS will be useful in the model-based approach and the prediction in, for example, epidemiology remains to be seen. The desired future development of GIS requires a switch of emphasis from data and information to knowledge. *(Int J Circumpolar Health 2004; 63: 9-24)*

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INTRODUCTION

Circumpolar areas offer interesting opportunities for studies of health in unusual environments that differ significantly from those in the western industrialized world. There are growing interests and international collaboration in the field of circumpolar health research. The developments in computing technology, statistics and data open up interesting possibilities for epidemiological studies of geographic orientation in circumpolar areas. In such studies, maps are fundamental tools for detecting abnormal spatial patterns of health outcomes and environmental risk factor associations, and therefore, spatial analysis techniques and methods will grow in importance.

A visual display of quantitative data and cartography has a long history, and there are numerous examples of excellent mapping work done in the past (1). Before computer-assisted mapping tools were available, all kinds of mapping had a number of limitations. One of the limitations was the difficulty of handling large quantities of information. It has been only since 1960s, following the advent of the digital computer, that quantitative thematic mapping has started to flourish and made the emergence of GIS (Geographical Information Systems) possible (2). GIS is a tool for linking and visualizing geographically referenced data from different sources, in which a geographical data element is used to provide a reference for the statistical or non-locational data element. It consists of topological and attribute databases together with procedures and techniques for data collection, up-dating, query, spatial analysis and modelling (2-4). With GIS, it is possible to link together the data of research interest and background variables (all forms of geographically referenced information), such as census, socio-economic and environmental data on the population, according to map coordinates. GIS has also been described as the technological aspect of a new discipline, geographic information science (5), which in turn is defined as 'research on the generic issues that surround the use of GIS technology, impede its successful implementation, or emerge from an understanding of its potential capabilities'.

Recently, GIS has emerged as an innovative and important component of many projects in public health and epidemiology (6). GIS has proved to be useful for epidemiological research purposes, decision-making, planning, management and dissemination of information. GIS helps to show regional variation in health problems, environmental risks and the use of health services and reveals abnormal patterns. GIS applications related to health have been introduced and used in, for example, the surveillance and monitoring of vector-borne and water-borne diseases (7-14), in environmental health (15-18), in modelling exposure to electromagnetic fields (19, 20), quantifying environmental hazards and their influence on public health (21-24), predicting traffic accidents and modelling traffic accident risk estimates (25-27) and for policy and planning purposes (28-32). In Finland, for example, GIS systems have been used in health services research (33) for studying small-area variation in mortality in an urban area (34) and in mapping studies of non-communicable diseases (35-37). Remote sensing and GIS have also increased their importance and utility in health-related studies (38-46).

Although disease-mapping studies have flourished and grown in importance along with the development of computer technology and GIS (47), disease mapping already played an important role in medical geography and epidemiology in the late eighteenth century (48). Disease mapping methods were first used for communicable diseases in an attempt to identify the sources of infection and to describe the rate of spreading of disease (48). Mapping of chronic diseases started with the recognition that environmental factors play an essential role in their aetiology. Geographical epidemiological studies, in which health and environmental exposure data are analysed in fine geographical detail, represent an important new approach (49).

The aims and purposes of disease mapping are (50, 51):

1. to describe the spatial variation in disease incidence for the formulation of aetiological hypotheses;
2. to identify areas of unusually high risk in order to take preventive action;
3. to provide a reliable map of disease risk in a region to allow better resource allocation and risk assessment.

GIS in epidemiology continues to be most useful in basic mapping (52). GIS may also involve more sophisticated spatial analysis of disease occurrence and contributing environmental factors. However, the spatial analysis capability of GIS is argued to be rather limited and, therefore, the value of GIS for spatial epidemiology should be critically assessed and discussed. This paper provides a broad view of the use of GIS, disease mapping and spatial statistical methods in geographical and epidemiological studies of disease occurrence. The potential of GIS for epidemiology and epidemiologists is discussed critically, and some recommendations are presented.

Importance of spatial data and scale

Spatial data constitute the backbone of GIS. The number of geo-referenced data sets that contain information on the health status of individuals has increased tremendously during the past few decades (53). GIS also provides access to additional information from a wide variety of sources. For example, Global Positioning Systems (GPS) can be used to obtain the precise locations of point features on a map. Furthermore, GIS can process aerial or satellite imageries to allow easy integration of information of such parameters as temperature, soil type, and land use and determination of spatial correlations between potential risk factors and the occurrence of diseases. The use of GIS, however, by no means overcomes two major concerns: the availability and quality of data. It is very important to understand the nature of errors in spatial data and the effect they may have on the quality of the analyses made with GIS.

In GIS, the spatial scale of analysis can be chosen freely, though naturally within the limitations of the given data. The scale of analysis or the level of aggregation is a trade-off between specificity and precision: the smaller the area, the more specific and relevant are the findings to the local population, but the greater are the imprecision and the potential for bias (52). Furthermore, many data sets exhibit different spatial patterns when viewed at one spatial level compared to another, which is known as a 'scale' effect (54).

It is becoming clear in the field of public health that health information (e.g. data) aggregated by political or other administrative areas are inadequate to address many public health concerns (53). Communicable and non-communicable diseases do not recognize areas or borders defined for administrative or political purposes, and a finer geographical scale of study is thus often more appropriate for epidemiological purposes. However, although there is a growing demand for finer-scale geo-referenced health data in epidemiological studies, the use of administratively organized spatial data is still of importance. The availability of administratively organized spatial data is much better than that of data of high spatial resolution. Health information is still, and will be for a long time, statistically generalized by administrative areas for the use of public health authorities and politicians and, of course, the general public. Any changes from generalized (municipalities, provinces) towards specific (1 x 1 km grid cell) information - although relevant from the epidemiological point of view – may lead to misunderstanding of the information. Also, the costs of data rise along with the spatial resolution capacity and the quality, and in many cases, the high costs of spatial data may be an obstacle in geographical health research.

Thus, whatever the choice of spatial resolution, it is artificial and, to variable extents, fails to "capture" people's everyday living environment. People do not live in a world of "provinces" or "1 x 1 kilometre grid cells". Anyway, administrative and political areas are still important from the viewpoint of national or regional health politics and administration. High-resolution spatial data also pose the question of conflict between individuals and administration. The use of high-resolution spatial data may endanger the privacy of individuals if used incautiously. None of us want to be identified on maps or in statistics by the authorities or by fellow citizens.

Not all maps are equal

The representation of disease incidence data can vary from simple point maps for cases and pictorial representation of counts within tracts to the mapping of estimates from complex models aiming to describe the structure of the disease events (51). Disease maps, the pattern of description and the presentation of spatial disease distribution can be divided into dot, diagram, choropleth and flow maps (15). Dot maps are able to show each health event with the resolution of a pair of coordinates, x and y. Choropleth maps are used to display mortality or morbidity rates for defined geographical units by colouring, shading or hatching, whereas flow maps are able to show the distribution dynamics of health events in time and space, and diagram maps provide added value to the presentation of quantitative data within a map.

Depending on the quantity and quality of data and the methodology used in the analysis, a given map may be useful or misleading. Discrimination between these two alternatives must be of great importance. The two main conventional approaches are maps of standardised rates and maps of statistical significance (55, 56). The former has the advantage of providing estimates of the parameters of interest (disease rates), but raises some problems. When the area has a small and unevenly distributed population and when the number of cases is small, variation in the observed number of events exceeds that expected from Poisson inference. The problem is exacerbated in the case of rare diseases, such as uncommon cancers, and outcomes, and when the method of presentation is a choropleth map. Maps of significance involve a different problem. The more extreme levels tend to occur in the areas with the largest populations, and this time, in contrast, more common cancers may show more geographical variability than rare cancers (56).

Various smoothing methods are used to avoid the problem of rate instability. The simple but unattractive form of smoothing is to choose larger geographical study units in order to achieve greater stability of rates. It cannot be recommended, however, because it involves the idea of discontinuity of geographical boundaries and hides important information of variation in rates on a smaller geographical scale. Precision can also be improved by aggregating over time. There are numerous methods of smoothing that provide more or less continuous depiction of rates across a map based on statistical techniques, such as Bayesian smoothing (57, 58), or GIS methods, such as local-area averaging, or geostatistical smoothing methods, such as Kriging (59).

The choice of map colour or hatching is of great importance as it helps to transform numerical information into an informative map. It is also important to make a decision on the number of categories and the choice of cut-off points (60). In some cases, the primary aim of classification is to provide the reader the maximum available information, and the choice will depend on whether or not the scale is data-dependent. In the case of several maps, the need for comparability may arise and the scale may be the same for all maps (i.e. independent of risk distribution). It is also easy to intentionally give the reader incorrect or even false impressions with maps and mapping techniques. Using appropriate colours and classifications, the disease can be concealed or highlighted in line with the current (political) intentions. In this respect, disease maps may convey a politically hidden agenda and partly reflect societal ideas and values.

Much of the "power of GIS" in health issues is based on its spatial analysis capabilities (6). Spatial analysis refers to the ability of the analysis to manipulate spatial data into different forms and to extract additional meaning as a result. It encompasses a variety of methods and procedures developed in different disciplines. A quantitatively-based framework for spatial analysis can be categorized into three broad classes (61): visualization, exploratory data analysis and model building. These vary in complexity from simple map overlay operations to statistical models, such as diffusion models (6). In the use of GIS, it is also important to differentiate between two approaches almost opposite to each other: on the one hand, the research work with scientific aims and methods, and on the other hand, the practical requirements for data processing and visualization of spatial data (62).

Public health professionals who are not very familiar with the statistical issues related to disease mapping increasingly use GIS. They are prone to the 'using one's brain' mode of investigation (63). This means, for example, that spatial data are put on GIS and thematic maps are produced to visualize the spatial relationships between health outcomes and several environmental factors, and finally, the striking patterns possibly found on the map are used to formulate explanatory hypotheses. Such investigation formulates hypotheses to explain an apparent pattern whose existence has not been confirmed.

A few insights into spatial statistics and modelling

Although visual analyses (mapped evidence) strengthened with exploratory analyses are most often sufficient for epidemiologists, quantitative modelling of disease distribution is needed to test formally certain hypotheses or to estimate relationships between the measure of disease incidence and, for example, environmental covariates. GIS can be useful in generating data for input into epidemiological models, displaying the results of statistical analysis, and modelling processes that occur over space (6). However, it is argued that the ability of statistical analysis and modelling is rather limited within GIS (64, 65). Most often, data need to be entered into separate software applications for statistical analysis and for model building, after which the processed data must be returned into GIS for the design and production of cartographic outputs.

Regardless of whether simple mapping methods or advanced spatial models are used, the ultimate goal must be differentiation between meaningful and spurious information. Straightforward use of classical statistical modelling that assumes independence of events may lead to less desired results in spatial epidemiology. Spatial relationships based on proximity and relative location form the core of the spatial analysis and spatial statistical models are therefore based on the idea of spatial dependence; in other words, disease incidence in one area is likely to spatially correlate with that in the neighboring areas (61). Without this presumption, there would be no "spatiality", and it would be appropriate to show the results in a tabular form (e.g. a list of all areas) without map topology (62).

A good statistical model is able to describe the "mechanism" that produces observations (the mechanism behind the data). The concept of probability and the way we interpret it is fundamental to our understanding and interpretation of occasional incidents (62). Frequentist methods regard the value of the phenomenon of interest as a fixed, unvarying (but unknown) quantity without a probability distribution (66). They calculate confidence intervals for this quantity or the significance tests of the hypothesis concerning it. However, the frequentist approach, whereby probability is seen as a set of trials, is not fully compatible with ecological research designs, which assume that there is only one realization of events, and which cannot be repeated (62). What should we do if we wanted to make reliable evaluations of the 'true' disease risk in a certain area in a certain year in the past?

The concept of probability in a Bayesian framework differs from the frequentist approach. Probability represents a state of knowledge in a Bayesian framework (67). In the Bayesian approach, the probability distributions used for inference do not represent a real property of the topic of interest, but only a certain state of information about it. Bayesian methods are based on the idea that unknown quantities, such as population means and proportions, have probability distributions (66). Bayesian analysis allows us to make inferences from data using probability models for quantities we observe and for quantities we wish to know (68). A Bayesian analysis starts with a 'prior' probability distribution ('before data') for the value of interest (a true relative risk) based on previous knowledge, and new evidence is then added into a model to produce a 'posterior' probability distribution ('after data') (69). The Bayesian approach takes into account not only the raw data but also any prior knowledge available that supplements the data. The prior information may include all possible objective or subjective evidence, such as experience, results from previous studies and data. When new evidence or information is discovered, Bayesians update their equation. The Bayesian approach also presumes that neighbouring areas are more likely to be similar than remote areas.

The use of GIS along with Bayesian spatial modelling would undoubtedly bring added value to spatial epidemiology. Applications of Bayesian methods to disease mapping, risk assessment and prediction within spatial epidemiological research are numerous (70-72). Bayesian modelling techniques can be successfully used in descriptive mapping analyses to produce, for example, maps of posterior means (smoothed incidence values) and maps of posterior probabilities (73). However, up till now, there are not many software packages suitable for Bayesian analyses, and the building of complex spatial models therefore requires lots of specialist programming work (66).

DISCUSSION

Is GIS of any added value in studies on spatial patterning of health? GIS undoubtedly offers epidemiologists a 'new' fascinating tool full of promises, but if poorly used, it can do more damage than good (74). Much of the added value of GIS depends on the availability of valid, accurate and complete spatial data. At the small area level, however, even relatively minor inconsistencies might have a major impact on the findings. Nowadays, geo-referenced data are abundant and continuously increasing. GIS can play an effective role in handling large volumes of spatially referenced health data routinely collected on small spatial scales. In cases where such databases are not available, GIS can provide other forms of data. GIS is capable of using remotely sensed satellite data, and locally global positioning systems (GPS) are a feasible way for spatial data capture.

Animation with GIS, for instance, is an effective method of depicting the spread or retreat of disease over space and time (6). The resurgence of new and old communicable diseases is challenging the achievements in health. One quarter of all deaths and 30% of the global burden of disease are due to infectious diseases (75). GIS can be an effective tool for public health authorities and epidemiologists in showing and monitoring diffusion patterns of communicable diseases and in searching for infectious agents.

Technological and social changes influence the types of risk factors to which populations are exposed, typically shifting the major causes of death and disease from infections to chronic, degenerative diseases (76). Non-communicable diseases are estimated to cause over 70% of all deaths worldwide by 2020, compared with an estimated 15% of deaths from communicable diseases (77). The mapping of geographical variations in the risk of non-communicable diseases aimed at advancing etiological hypothesis will increase the importance of epidemiological studies on geographical orientation in the future, and GIS data, techniques and methods will be the focus of interest in many such studies. Compared to statistical tables, GIS can reveal spatial variations and distributional patterns of non-communicable diseases more effectively (48). With the assistance of disease maps, low- and high-risk areas can be highlighted, and environmental factors (physical and/or socio-cultural) contributing to the process of causation can be related to diseases. Furthermore, GIS techniques, such as overlay techniques, are suitable for searching simultaneously spatial patterning and the risk factor associations of two or many diseases of interest.

Although the spatial analysis techniques of GIS can incontrovertibly add a great deal to the research on contagious and non-communicable diseases, they must be used with care and statistical awareness. We should always ask which map is correct? In an absolute sense, they all are. Which one should we use? If a map is evaluated to be statistically unusual, it is justified to infer a theory or hypothesis to explain the spatial relationships. However, there is no proof of causation in the information conveyed by maps (63). GIS undoubtedly plays a critical role in data management and the visualization process, but spatial statistics are needed to determine whether the pattern on these maps is somehow unusual.

What methodology should we use in spatial analyses of diseases? No methodology of choice can be recommended in general. The methodology should be chosen in view of the data and the hypothesis concerning the research problem. In most cases, the first step is to carry out a descriptive analysis, followed by more specific and problem-dependent analyses involving parameter estimation and hypothesis testing. Traditional methods and GIS, such as maps of standardized disease rates, are often appropriate for descriptive data analysis and for investigating the first-level associations with disease and, for example, environmental risk factors. However, the analytical capacity of GIS is mostly inadequate even for the requirements of basic epidemiological spatial analyses, and whenever there is a need for more sophisticated study designs that require multivariate techniques and statistical modelling, we probably find GIS much less flexible (64, 65). The use of spatial statistical methods and modelling, such as Bayesian techniques, in epidemiology may open up many possibilities and avoid many of the problems related to disease mapping.

Regardless of the degree of sophistication of the statistical methods or the goodness of the model fitness, the geographical mode of investigation and disease mapping are always highly problematic. In many instances, covariate effects are the central issue in spatial analyses, and the spatial structure in the residuals can be thought of as a proxy for many unidentified covariates. However, ecological bias occurs when the background rate of disease varies between populations because of differences in the distribution of other risk factors, or when the effects of a particular 'exposure' are modified by other factors (52). Using a geographical analysis, it is only possible to get a suggestion that there might be a connection between an environmental agent and the disease occurrence. Ecological studies are most useful for generating and testing hypotheses (i.e. qualitative identification of an association) and less applicable to quantitative estimation of the strength of an exposure-response relationship (78). In particular, geographical analyses of the distribution of disease frequency and risk factors can be beneficial, especially if the exposure-disease association is specific, the latency is short, and the exposure is spatially defined.

In the modern industrialized world, people of all ages are very mobile. Children commute between home and day care or school, and the working population commute between home and work almost every day. A considerable proportion of the population move from one region to another within the municipality or country, or from one country to another, every once in a while. Therefore, people expose themselves to different risk factors in different locations, and the relationship between catching a disease and the potential environmental risk factor is difficult to prove reliably (79). Thus, all the exposures and risks experienced earlier in life may become associated on maps with an inaccurate geographical location and may easily lead to erroneous conclusions and aetiological hypotheses without individual-level information of the exposure history (62, 79). Individual-level follow-up studies are needed to gain information of the measurement of real exposure, but are, in many cases, laborious and costly. However, it would be fascinating to carry out analyses with a spatio-epidemiological model, which would be more based on individual-level data than coarse spatial data. These individual-level data can be gathered, for example, by questionnaires or by using modern GPS and GIS technologies. Such a database can function as an individual-level spatial exposure history and undoubtedly strengthen the spatial analyses aimed at search for the causality of the disease.

The descriptive stage of analysis is concerned with the description and mapping of health-related phenomena. The analytical stage tries to step forward by searching for explanations and seeking laws behind the observed spatial pattern. The predictive stage uses a model-based approach to make predictions. It is promising that spatial statistics and GIS technology have slowly started to merge (73). However, whether GIS will be useful in the model-based approach and the prediction in, for example, epidemiology remains to be seen. The desired future development of GIS requires a switch in emphasis from data and information to knowledge.

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