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GEOMEDICAL APPROACHES BASED ON GEOGRAPHICAL INFORMATION SCIENCE
GIS and Spatial Analysis for Health Researches

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ABSTRACT

The present paper is a brief review of the geomedical approaches focusing on GIS and spatial analysis for health researches. The content consists of the three subcategories; detecting spatial clustering of disease, monitoring and analysis of regional inequalities of health status, and modelling spatial diffusion of diseases. As well as the fundamental ideas of the approaches, some useful resources including software and websites are shown for readers who are interested in the themes.

1. Introduction

1.1 The Aim of the Paper

GIScience is now characterized by the three major technologies; RS (Remote Sensing), GPS (Global Positioning System) and GIS (Geographical Information System). Coupling the long tradition of spatial analysis in medical geography and epidemiology with these new technologies, geomedical approaches, referred as spatial epidemiology (Elliott et al. 2000) or spatial health research (Lepper et al., 1995), are enhanced. Especially GIS offers a new environment for spatial analysis of disease by integrating many kinds of data and analysis. Considerable number of publications of health researches based on GIS technologies has appeared since the late 1990's (Gatrell and Löytöonen, 1998; Savigny and Wijeyaratne, 1995). In addition, anthologies of GIS study often include some sections about epidemiological issues (Longley and Batty, 1996; Longly, 1999). These reflect that the geographical and spatial approaches in health studies are re-evaluated and empowered by GIScience. This paper summarizes some fundamental ideas and developments of the geomedical approaches with GIS and its related analytical perspectives. At the same time, I would like to show some useful resources for unfamiliar readers who are interested in the themes.

1.2 Why GIScience for Health Researches?

The reasons why health researchers applied the new geo-based technologies to analysis of health are mainly divided into the three aspects. First the geo-based technologies are expected to be new and effective tools to collect the information that is useful for epidemiological analysis. GPS is a handy tool to acquire the locational information in the field. Application of RS is focused on the relationship between environment and health related problems in small scales (Albert et al., 2000; Hay et al., 2000). The habitat detection of hosts of

Table 1 Type of User and Health GIS (HGIS)

Type of User	User Demand	Type og GIS	Typical Health GIS
HGIS Specialist	Analysis/ Development	Large and Flexible	Commercial GIS for General Use (ARC/INFO, ArcView, MapInfo)
			Specific Analytical Application (GAM, SaTScan, Crimestat, DismapWin)
General Researcher Using HGIS	Analysis/ Specific Use	Compact and Manageable	Customized GIS (Epimap2000, WHO Health Mapper)
			Web GIS (Gather, Health Map of Japan)
Management/ Decision Maker	Evaluation/ Easy to Use	"Small and Beautiful"	
Target Group/ Non-Specialist	Information/ Well Accessible	"Small and Beautiful"	

This table is adapted from Scholten and Padding(1990) to Health GIS.

infectious diseases like malaria is a typical example. GIS has effective functions to digitise non-digital information (e.g. paper maps) and integrate many data sources including RS, and GPS. Address-matching is an important function of GIS to plot geographical positions automatically following the records of address names in a database. The function has developed based on street-base cadastral systems in North America and Europe. Unfortunately, Japanese non-street base addresses make such development difficult.

Secondly GIS is used for a platform to perform spatial analysis of geographical datasets of disease/health. The approach tends to include disease mapping (Lawson and Williams, 2001) and spatial analysis (spatial statistics and spatial mathematical modelling) (Thomas, 1992) in order to find regularities or anomalies in geographical distributions of disease/health. Computational advances have enhanced spatial analysis more sophisticated and practical than ever. These encompass techniques of drawing reliable disease maps by Bayesian estimation, automated detection of anomalous geographical concentrations of disease, and association modelling to explain disease distribution like regression analysis. Some specialized tools are distributed on Internet to apply these analytical techniques to researcher's own datasets.

Thirdly GIS gives good presentations to decide some actions in heath care and medical interventions. Maps are easy-to-read visualization for both specialists and non-specialists. Especially the development of web-GIS encourages sharing key geographical knowledge related to health issues to general, medical and political end-users to empower them.

Let GIS for health researches call simply HGIS (Health GIS). Table 1 summarizes the relation between HGIS users and GIS system required. Representative application software is also presented in the Table.

2. Detecting Spatial Clusters of Disease

2.1 Snow's Cholera Map

One typical usage of GIScience for health can be illustrated by using the notable story, John Snow's Cholera map in the mid 19C. Working in the Soho district in London attacked by a severe cholera epidemic, Snow(1855) dotted the Cholera death on a map. Then he showed that the distribution of the death concentrated around the one pump located in the Broad Street. He had already advocated the existence of micro organisms by which cholera was transmitted among people, so that he suspected drinking water from the pump triggered the epidemic in the district. By using the map and thinking spatially, he confirmed that the pump propagated the epidemic and must be stopped to use. The map would be an effective and crucial presentation for insisting the validity of his action to break the pump. According to the legendary story, the epidemic was ceased soon after the abandon of the water pump.

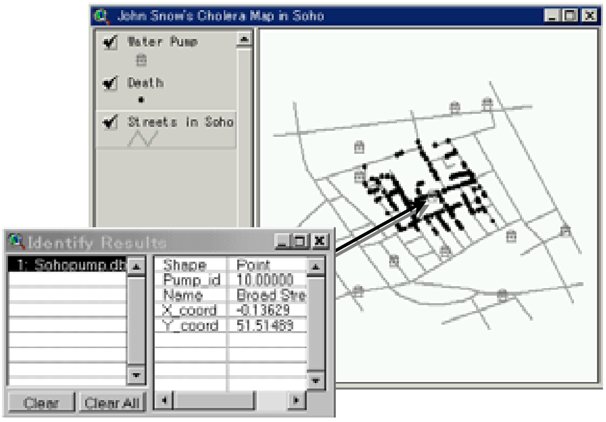

Figure 1 John Snow's cholera map using the CDC GIS data.
-Identification of the Broad Street pump by GIS-

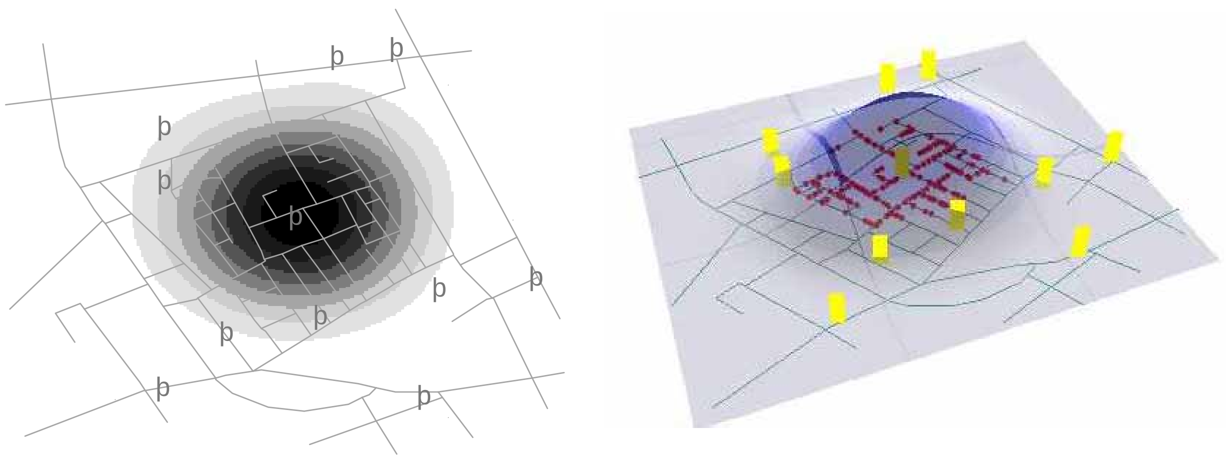

Figure 2 Kernel density estimation of cholera death.
Left: 2D, Right: 3D presentation

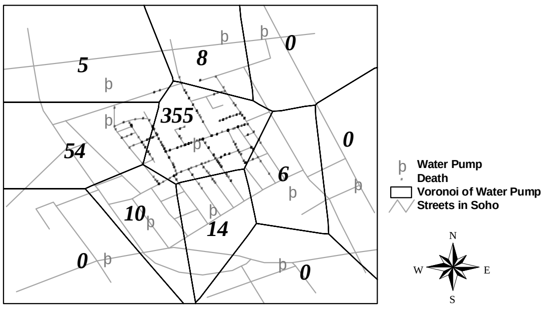

Figure 3 Voronoi diagram based on water pumps. Number in each polygon is the number of death inside the polygon.

2.2 GIScience Approaches to Snow's Cholera Map

If Dr. John Snow lived in the present time and different place, he could use GIScience techniques to employ his work efficiently. First he could find the position easily by GPS to find house locations with death. Or he might use address-matching system if there are good death registrations containing addresses. If there were not official maps, he could create a digital map by vectoring a high-resolution satellite image like IKONOS or digitising aerial photos in a GIS environment.

Secondly with GIS he could draw a dot map fast and apply spatial analysis, such as density estimation and overlay with the location of pumps. GIS provides an environment for exploratory spatial data analysis by which he could easily and interactively test a lot of hypotheses (Figure 1). It would help him to infer the reason why the epidemic happened and what actions were most effective.

Thirdly he could distribute his result to many people instantly via Internet, although he might have to blur the exact locations of death for protecting personal privacy. If some agency realized that a new monitoring program should implement such a work, it could build a web-GIS system by which end-users without detailed knowledge of GIScience could query the monitored data and find map results with a user-friendly interfaces.

2.3 GIS Data and Analysis of John Snow's Data

As showed earlier, the data collected by John Snow is a good example for explaining how GIS and spatial analysis work in epidemiological contexts. Cliff and Haggett (1988, 1996) applied many techniques including thematic maps and spatial statistics to the data. Recently CDC developed an epidemiological software package with a GIS component, Epiinfo2000 and distributes the GIS dataset of John Snow for tutorial. For detail, access http://www.cdc.gov/epiinfo/EI2000.htm. Although Epiinfo2000 does not have spatial analysis modules, we can directly use the data by ArcView GIS (ESRI Corp.). Figures 2 (density estimation of cases) and 3 (catchments area estimation for each pump) are examples of analytical functions of GIS applied to the data. These clearly show that the Broad Street pump is certainly located in the centre of the distribution of Cholera death.

2.4 Advanced Environments for Spatial Clustering

John Snow analysed only the distribution of cases. If the city area has high population density and we can ignore the uneven distribution of households, detecting of case concentrations would be meaningful. On the other hand, if population at risk is sparsely distributed, we should consider distributions of *rates* of cases and small number problem; the rates of cases become unstable due to the shortage of samples.

Openshaw's GAM (Geographical Analysis Machine) (Openshaw et al., 1987) overcomes such problems by a heavily computational manner. The system tests every possible centre position and size of anomalous cluster of cases based on spatial aggregation with circles. With this system, he found significant clusters of childhood leukaemia including one around a nuclear reprocessing facility in the North England. After Openshaw's study, several advanced tools have been developed and distributed for general use as below.

GAM/K Online by Openshaw
 The latest version of GAM. Web application.
 http://www.ccg.leeds.ac.uk/smart/gam/gamin.html
SaTScan by Kulldorff et al.
 Stand alone application program.
 http://dcp.nci.nih.gov/bb/SaTScan.html
CrimeStat by Levine et al.
 Stand alone application program.
 http://www.icpsr.umich.edu/NACJD/crimestat.html
Dmap by Rushton et al.
 Stand alone application program and GIS module
 http://www.uiowa.edu/%7Egeog/health/
SPLANCS by Rowlingson and Diggle
 Macro sets for S plus
 http://www.maths.lancs.ac.uk/~rowlings/Splancs/

3. Monitoring and Analysis of Regional Inequalities of Health

3.1 Visualization of Geographical Aspects of Health

Point data like John Snow's Cholera death contain useful information for detecting anomalous spatial concentration of cases. However, most of statistics reports only values aggregated by areal units. While the areal aggregation loses information of detailed geographical position, there are some merits. First it enables us to avoid the problem of personal privacy because of the lack of exact information of each case. Secondly areal aggregated data is easy to handle to map and analysis overall distribution. So areal maps (Choropleth maps) are quite common in showing regional differences of health status.

Figure 4 is a typical areal map for monitoring regional health. The darker an areal colour is, the higher the areal mortality is. The indicator to be mapped is standard mortality ratio (SMR) for elderly men (65-84yrs) as of 1990. The value is a simple OE ratio (observed number

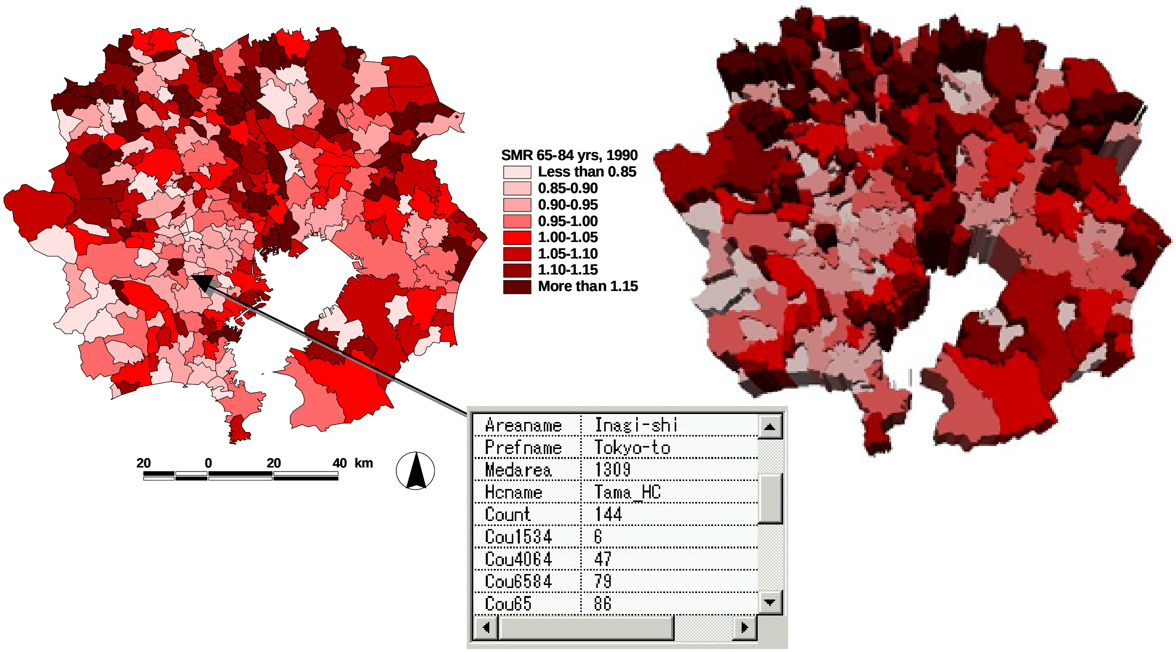

Figure 4 Choropleth Map (left) and its 3D presentation (right) of Standard Mortality Ratio, 65-84 yrs, Male, the Tokyo Metropolitan Area, 1990

of death / expected number of death) taking into account age structure. SMR is defined as below:

$$SMR_i = y_i / x_i = y_i / \sum p_{i,j} m_j \qquad (1)$$

where i is an index of area, y_i is the observed number of death, x_i is the expected number of death, $p_{i,j}$ is the number of population of j th age interval and m_j is the national average of death rate for j. If the value is higher than 1.0, the mortality is higher than the national average of mortality pattern. Again GIS provides an explanatory environment by which we can query areal dataset interactively with map drawing.

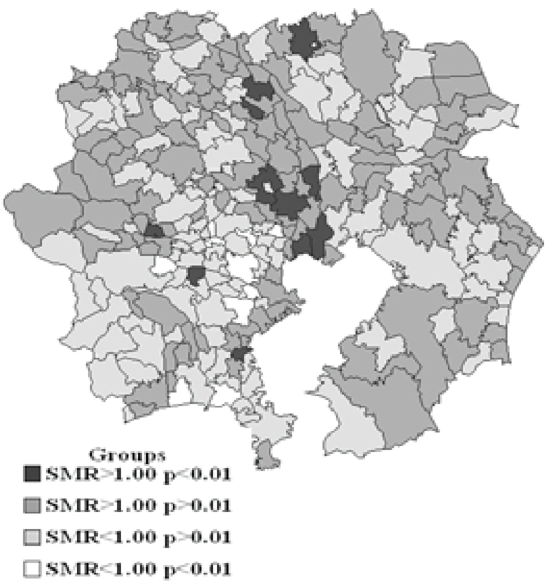

Figure 5 Poisson Probability Mapping (DismapWin)
Black: significantly higher than the national average.
White: significantly lower than the national average.
The significance is at the 0.01 level.

There are several issues to be considered for using such choropleth maps. First, different class intervals and shading/colouring schemes shifts viewer's impression of the distribution, even if the original data to be mapped is same. Mapmakers should try several ways of these settings to check the stability of the map's impression. 3D visualization with vertical axis in proportion to the magnitude of mortality is a way to avoid the arbitrary classification problem (see Figure 4 right).

Secondly, the numbers of cases and population at risk varies over space; so that areal indicators defined as ratio tend to be unstable. In order to resolve the problem, several approaches are developed.

(1) Probability Mapping
If we consider death as independent probabilistic event, we could test whether a number of deaths in an area could be happened by the mortality of national average (Choynowski, 1959). Poisson or binomial probability is usually assumed in the statistical tests (Figure 5).

(2) Bayesian Smoothing
Areal mortality index are shrinked to a prior expected value (such as the national average), based on the size of expected death. If an area has enough size, the shrinkage is ignorable. On the other hand, when the size is too small to calculate reliable death ratio, the shrinkage to a priori mortality level is prominent. Such flexible estimation is theorized by Bayesian manner (Devine et al., 1994; Marshall, 1991).

(3) Spatial Aggregation
Spatial aggregation is the simplest way to get stable regional estimators of mortality. The example of the

Tokyo metropolitan area clearly shows concentric and sectoral disparities of the mortality as the overall regional variation (Figure 6). Cluster analysis can be applied to construct homogeneous regions (regionalisation) of social indicators, such as demographic and occupational structure. Nakaya (2000) defined a statistical optimisation of the regionalisation for disease maps.

(4) Areal Cartogram
Large areal units tend to be located in peripheral parts and have few populations. As a result, regional variation of less populous areas, that is, distributions of unreliable ratios, are remarkable for map readers. Cartogram is made by transforming the areal size of map unit proportional to the size of population or other expected size of observation (Dorling, 1995). It provides a reasonable basis to assess regional variation of indicators affected by the demographic size of areal units.

3.2 Spatial Associations of Areal Health Data

Correlations between regional variables of areal units are called ecological correlations. Although aggregation biases the correlations in comparison with the individual level (ecological fallacy problem; Robinson, 1950), ecological correlation and regression analysis often provide useful information about the regional distribution of health indicators.

If the health indicators to be analysed can be considered as reliable, we can apply ordinary correlation coefficient and regression models. However as shown in the previous subsection, the condition is unsatisfactory in small area studies. Following the same assumption of the probability mapping, Poisson regression is a reasonable tool to associate between heath indicators and other explanatory variables (Lovett et al., 1986).

$$y_i = B_i \exp(\beta_0 + \beta_1 x_{1,i} + \cdots \beta_M x_{M,i}) + \varepsilon_i \qquad (2)$$

where i is an index of area, y_i is the observed number

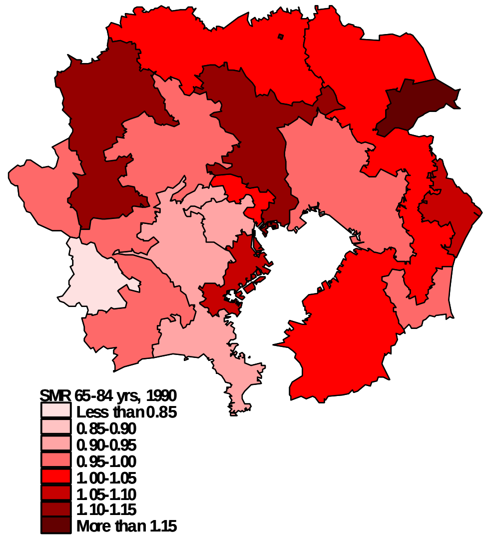

Figure 6 Choropleth map based on socially homogenous regions using cluster analysis.

of death, B_i is the expected number of death, β_k is the regression coefficient for the k th explanatory variable $x_{k,i}$ and ε_i is the Poisson random error term.

As an example, Figure 7 shows the distribution of ratio of “Professional and Technical Worker” (typically white-collar workers with high salary) to associate with the SMR distribution. The scatter plot (Figure 8) indicates a negative correlation. The calibration result of Poisson regression is as following.

$$y_i = B_i \exp(0.22_{(12.2)} - 1.58_{(-12.6)} x_i) \qquad (3)$$

where the numbers in parenthesis are t values for parameters. In this case, the regression coefficient is significantly negative at the 0.01% level. It indicates that suburbs of white-collar residential areas tend to show better health status (lower mortality). It should be noted that not white-collar workers but the residents in the suburbs characterized by high ratios of white-collar

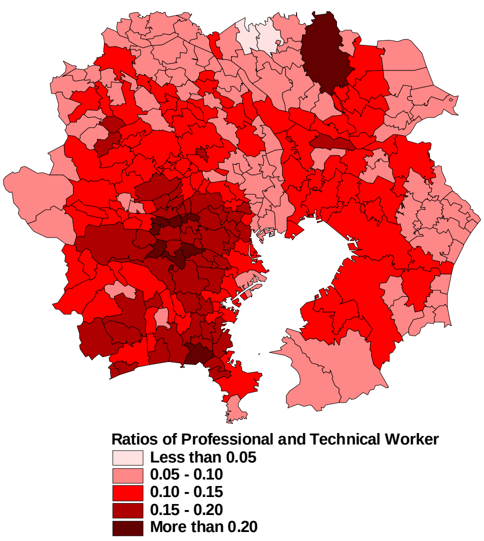

Figure 7 Ratio of Professional and Technical Workers

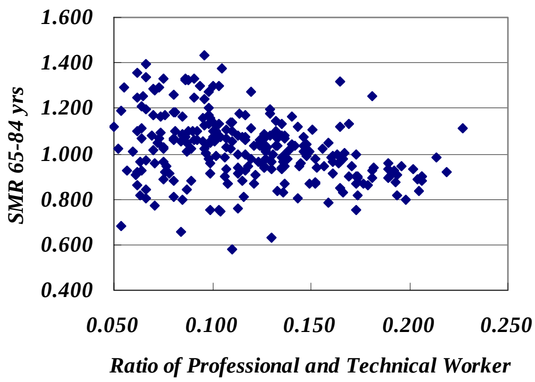

Figure 8 Scatter diagram showing a ecological correlation between “Ratio of Professional and Technical Workers” and SMR of elderly men

workers shows relatively better health status. For interpretations of the distribution disparities of the area, see Nakaya (2000).

Because the model is not perfect to explain the SMR distribution, as a usual step, residuals of the model are mapped. If the residuals are spatially autocorrelated (similarities of residual values among connected regions), assumption of the independent error term of the model would be violated. This indicates that estimated coefficient is biased and researchers should pursue more valid model, by adding another explanatory variables or another model. For further issues of disease mapping and the associative techniques, see Gatrell and Löytöonen (1998), Lawson (2001) and Elliot et al. (2000).

DismapWin, a MS-windows application for disease mapping and analysis, provides an interactive interface to carry out disease mapping, Poisson regression and Bayesian modelling. Several packages equip statistical functions with visualization such as mapping and scatter diagram for explanatory spatial data analysis (ESDA) of heath data.

DismapWin by Schlattman
  Stand-alone application program
  http://www.ukbf.fu-berlin.de/sozmed/DismapWin.html
SAGE by Jingsheng et al.
  Macro sets for ARCINFO
  ftp://ftp.shef.ac.uk/pub/uni/academic/D-H/g/sage/sagehtm/sage.htm
S plus SpatialStat & S plus for ArcView
  Commercial packages, S plus and ArcView modules
  http://www.uk.insightful.com
  http://www.msi.co.jp/splus/ (in Japanese)

3.3 Health GIS for Semi/Non-Specialized Users

The interface and data conversion procedures of spatial analysis packages are complex for users without knowledge of handling geographical information and spatial statistics. However, only for mapping and querying, customized GIS can prepare simple user-interfaces. In addition, databases ready for use are important in practice because it is difficult for individual to collect data supplemented by many kinds of sources. The HealthMapper developed by WHO and Unicef is one of the most ambitious attempt in the development of Health GIS. The GIS package is composed of simple user interfaces and large geographical database around the world.

Web GIS is a more efficient way to distribute fundamental information of health issues for non-specialists. End-users of web GIS do not need GIS, special packages, and database on their computers except for web browser like internet explorer or netscape. GATHER maintained by CDC provides web-based thematic mapping system. The web GIS has the data of national distributions of cancer mortality and locations of potentially hazardous waste facilities.

In Japan, the web page of Ministry of Health, Labour and Welfare has the browsing system of health indicators for each prefecture or municipality. A function of the system entitled *kenko map* (health map) produces maps of SMRs and participant ratios of cancer screening for each prefecture, although there is no special interface to overlay other geographical information. These systems dramatically improve to access the geographical data of health. It is expected that these systems contribute to sharing the recognition of their regional inequalities of health as an important public health problem among residents and officials of local health sectors.

Gather by CDC
  http://search.lycos.com/raf/default.asp
HealthMapper by WHO and Unicef
  The software can be downloaded by the website of WHPRO (WHO Western Pacific Regional Office). The database contains the information of only western pacific countries.
  http://www.who.int/emc/healthmap/healthmap.html
  http://bbs.wpro.who.int/healthmap/profile.htm
Kenko Map (Health Map) by Japanese Ministry of Health, Labour and Welfare
  http://statmap.mhw.go.jp/ (in Japanese)

4. Spatial Diffusion Modelling of Disease

4.1 Visualizing Spatial Diffusion of Disease

Hägerstrand distinguished neighbouring diffusion (from near to far places) and hierarchical diffusion (from large towns to small villages) from a lot of examples of spatial diffusion. The two patterns can be picked out in diffusions of infectious diseases. Figure 9 (left two maps) shows the diffusion of HIV in Japan from 1990 to 1999. Most of reports of HIV cases concentrated in Tokyo and its surrounding prefectures. At the same time, in large cities, such as Osaka and Fukuoka, HIV cases appeared in the early stage and increased constantly. These maps indicate, then, that the neighbouring and hierarchical diffusion process have worked in the AIDS epidemic in Japan. Gould (1993) and Smallman-Raynor et al. (1992) summarize spatial aspects of AIDS diffusion at different scales.

Time series mapping like Figure 9 is useful to think of the future of regional health status. Animated mapping is another new way to show vividly such a dynamic aspect of disease distribution. The Website of Sentinel Network of the French General Practitioners provides various animated maps for influenza epidemics in France, based on the national surveillance reports. For details, access http://www.b3e.jussieu.fr/sentiweb/.

4.2 Spatial Epidemiological Modelling

Regions are connected and interacted each other by inter-regional flows. It leads to inter-regional contacts of people to regulate spatio-temporal patterns of diffusion processes. Gravity models specify the inter-regional flows as below.

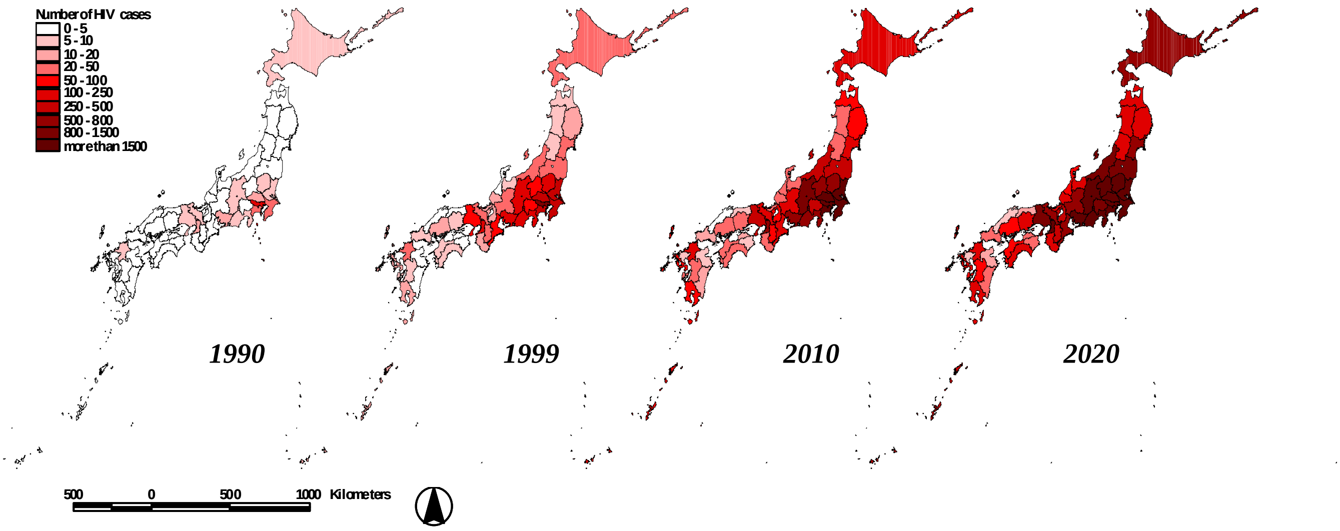

Figure 9 Spatial sequences of HIV diffusion in Japan
Reported cases for 1990-1999 / predicted cases for 2010-2020

$$T_{ij} = \alpha P_i P_j / D_{ij}^{\tau} \quad or \quad k P_i P_j \exp(-\tau D_{ij}) \tag{4}$$

where T_{ij} is the size of flow between region i and j, P_i is the size of population of region i, D_{ij} is the distance between the regions i and j. α and τ are parameters. The model captures the size and distance decay effect in the inter-regional flows. These characteristics create the neighbouring and hierarchical channels to propagate infectious diseases.

Taking account into the model, we can build space-time series model to trance back and predict the future distribution of infectious diseases (Nakaya, 1994; Thomas, 1990). A simple model for HIV diffusion in Japan is specified as following:

$$I_{i,t+1} = \mu I_{i,t} + \beta_i S_{i,t} \sum_j I_{j,t} / P_j m_{ij} + \gamma O_{i,t} \tag{5}$$

where

$$S_{i,t+1} = \nu S_{i,t} - \beta_i S_{i,t} \sum_j I_{j,t} / P_j m_{ij} - \gamma O_{i,t} \tag{6}$$

$$m_{ij} = P_i P_j \exp(-\delta D_{ij}) / \sum_k P_i P_k \exp(-\delta D_{ik}) \tag{7}$$

where $S_{i,t}$ is the number of susceptibles of prefecture i at year t, $I_{i,t}$ is the number of infectives of i at t. In prefecture i, each susceptible contacts β persons sufficient for infection of HIV. Following the gravity model, the contacted persons are allocated for each prefectures where the ratio of infective is $I_{j,t}/P_j$. μ is the annual survival rates of infectives. $O_{i,t}$ is the number of the susceptibles of prefecture i visiting foreign countries and γ is the infectious rates acquiring HIV in foreign countries. ν is the reproductive rates of i at t.

We could ignore the susceptible dynamics at the stage that the infective rates are sufficiently small. Let us simplify it to use the exogenously predicted population for each prefecture as below.

$$S_{i,t} = \hat{P}_{i,t} - I_{i,t} \tag{8}$$

Because it is expected that the speed of infection is varied due to population density and behaviour properties, the model estimate the regional variation of the infection parameter, β, using a localized calibration technique, GWR (Geographically weighted regression) (Fotheringham et al. 1997). The terminal model fits well the past diffusion sequences. The details of the calibration procedure are omitted because of the lack of the space. Figure 9 shows the spatial prediction of HIV cases at 2010 and 2020 by the model. The trends of neighbouring and hierarchical diffusion will last for the next several decades. The linkage of such space-time epidemic modelling and GIS is still in development.

5. Conclusion

Although GIS and spatial analysis are not all-around tools for health study, space and region are certainly important concepts for health issues. We live in geographical space so that health problems emerge in a geographical and spatial context. GIS and spatial analysis empowered us to think of the contextual effects. Linkage between epidemiological analysis and health care resource allocation is another important task of GIS for health (Gatrell and Senior, 1999). GIS and spatial analysis contribute to actions to attain better health situation in various ways. In North America and Europe, a lot of applications of GIS and spatial analysis to health researches are now widely accepted in practice (Lang, 2000). The condition of geomedical approaches in Japan is, however, just at the early stage in the diffusion process of the innovation.

For encouraging the geomedical approaches in Japan, it should be emphasized to share the beneficial aspects of the approaches and accumulate resources of GIS and spatial analysis for health. Specialized promotions are also desired, including research projects with partnership between spatial and medical scientists and maintaining laboratories of GIS and spatial analysis for health researches.

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