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Identification of environmental determinants for spatio-temporal patterns of norovirus outbreaks in Korea using a geographic information system and binary response models

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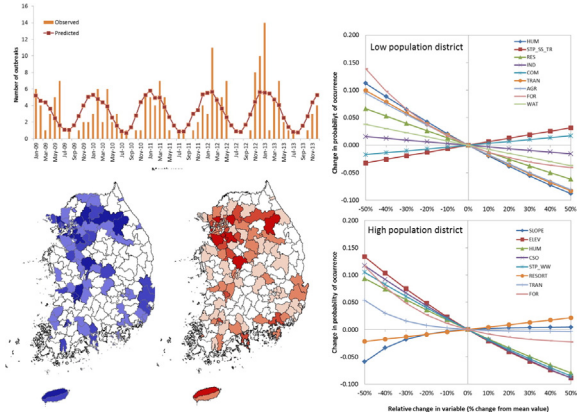
HIGHLIGHTS

- A GIS and binary response models were used to predict norovirus outbreaks' patterns.
- Strong winter seasonality of norovirus outbreaks was confirmed.
- Local sewage treatment plants favored norovirus outbreaks.
- Compactness of the land development affected the occurrence of norovirus outbreaks.
- Overcrowding of people and cold temperature synergistically increased norovirus outbreaks.

GRAPHICAL ABSTRACT



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ABSTRACT

Although norovirus outbreaks are well-recognized to have strong winter seasonality relevant to low temperature and humidity, the role of artificial human-made features within geographical areas in norovirus outbreaks has rarely been studied. The aim of this study is to assess the natural and human-made environmental factors favoring the occurrence of norovirus outbreaks using nationwide surveillance data. We used a geographic information system and binary response models to examine whether the norovirus outbreaks are spatially patterned and whether these patterns are associated with specific environmental variables including service levels of water supply and sanitation systems and land-use types. The results showed that small-scale low-tech local sewage treatment plants and winter sports areas were statistically significant factors favoring norovirus outbreaks. Compactness of the land development also affected the occurrence of norovirus outbreaks; transportation, water, and forest land-uses were less favored for effective transmission of norovirus, while commercial areas were associated with an increased rate of norovirus outbreaks. We observed associations of norovirus outbreaks with various outcomes of human activities, including discharge of poorly treated sewage, overcrowding of people during winter season, and compactness of land development, which might help prioritize target regions and strategies for the management of norovirus outbreaks.

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1. Introduction

Foodborne diseases remain of high concern worldwide due to their impacts on human health and the economy in many geographical regions (Hallman et al., 2009; Newell et al., 2010; Tauxe et al., 2010). In the United States, it was reported that 48 million people suffer from foodborne diseases each year, and the resulting annual cost ranges from USD 51.0 to 77.7 billion including medical costs, productivity losses, and illness-related mortality (Scharff, 2012). In the United Kingdom, foodborne diseases are responsible for about 10% of morbidity and mortality, and the annual economic burden attributed to foodborne diseases was estimated at £6 billion (equivalent to USD 8.7 billion) (Rayner and Scarborough, 2005). In Korea, the annual total burden of foodborne diseases was estimated to be about USD 9500 million (Shin et al., 2010).

Foodborne diseases are caused by consuming foods or beverages contaminated by pathogens, chemicals, and parasites (Tauxe et al., 2010). Currently, while over 200 microbial, chemical or physical agents that cause foodborne illness have been identified (Acheson, 1999; Newell et al., 2010), 50% to 60% of the causative agents of foodborne diseases remain unknown (Tomkins et al., 1999). Despite the limited understanding of foodborne sources associated with specific diseases, many epidemiologic studies have indicated that noroviruses are the leading cause of outbreak-associated gastroenteritis worldwide (Baert et al., 2011; Trivedi et al., 2012; Lai et al., 2013). In the United States, it was reported that noroviruses are the most common cause of foodborne illness and the fourth common cause of foodborne death (Scallan et al., 2011). In Korea, noroviruses were the most reported cause of foodborne outbreaks in 2006–2014 (KMFDS 2015).

Noroviruses are single-stranded RNA viruses that are extremely contagious, causing a sudden onset of vomiting and diarrhea (Rohayem, 2009). Noroviruses are stable in the environment and can be easily transmitted through a fecal-oral route, or by ingestion of contaminated food or water (Trivedi et al., 2012). Meteorological factors such as rainfall patterns, temperature, humidity, and winds can largely affect the transmission pattern of viruses by altering the survival rate and transferability of viruses in the environment, resulting in various epidemiological outcomes (FAO, 2008; Tirado et al., 2010; Lopman et al., 2012). In particular, previous studies showed that cold and dry weathers are associated with an increase in the norovirus infection rate (Lopman et al., 2009; Rohayem, 2009; Inaida et al., 2013). Besides the spatio-temporal variability of meteorological factors, the human-made physical features of geographical areas such as population density, water supply and sanitation systems (e.g. public sewage treatment plants, public night soil treatment plants, and sewer networks), and spatial distribution of pollutant sources, contribute to the exposure patterns of infectious agents, resulting in different geographical transmission patterns of an infectious disease (Jerrett et al., 2009).

Of great interest to epidemiologists have been spatio-temporal clustering and transmission patterns of infectious diseases because this information can help the timely detection and management of health risks (Kulldorff and Nagarwalla, 1995). A small number of studies have been conducted on the spatio-temporal transmission patterns of norovirus incidence or prevalence. These studies examined the role of spatial proximity in norovirus transmission in the hospital environment (Harris et al., 2013), spatial or temporal patterns of norovirus outbreaks associated with climate conditions on a nationwide scale (Lopman et al., 2009; Inaida et al., 2013), and tracking the spatial diffusion of norovirus infection rates using syndromic data with the goal of developing an early warning system (Cooper et al., 2008). Due to the well-recognized winter seasonality of noroviruses, most studies have primarily focused on the effects of seasonal factors such as temperature and humidity on the spatio-temporal transmission patterns of the norovirus infection. However, to the best of our knowledge, the role of the natural and human-made environmental factors of geographical areas has been rarely studied in the norovirus literature.

In this study, we assessed natural and human-made environmental factors that favor the occurrence of norovirus outbreaks using nationwide disease surveillance data. The environmental factors considered as candidate explanatory variables for differences in spatio-temporal outbreak patterns across geographical locations include climate conditions, geographical features, demographic characteristics, conditions of public water supply and sanitation systems, and land-uses. We used a geographic information system (GIS) and statistical approaches to investigate whether the norovirus outbreaks are spatially patterned and whether these patterns are associated with specific environmental variables. The specific objectives of this study are to 1) examine whether the norovirus outbreaks are spatially patterned, and thereby to evaluate the role of geographic proximity in spreading noroviruses between administrative districts, 2) to identify the site specific natural and human-made environmental factors favoring the occurrence of norovirus outbreaks using binary response models, and 3) develop the best binary response model that can predict spatio-temporal patterns of norovirus outbreaks with a reasonable accuracy.

2. Methods

2.1. Surveillance data of norovirus outbreaks

In Korea, norovirus outbreaks are monitored through a nationwide electronic surveillance system overseen by Korea Centers for Disease Control (KCDC). Since its development in 2007, the surveillance system periodically receives reports from clinical agencies to update the database containing sporadic incidents (patients) and outbreaks (the occurrence of more than one incidents that are found common in the original infection source based on the epidemiologic study) of norovirus on a daily basis. The surveillance data were obtained from KCDC for the 5 years from 2009 to 2013 with a spatial resolution of county-level administrative districts (a total of 277 geographical units ranging from 3 to 1817 km^2 in area); data for the two years' test running period (2007–2008) of the surveillance system were excluded to avoid potential errors originating from the data uncertainty during the test period. In general, the daily count of outbreaks for each administrative district was not sufficiently large for statistical inference and we therefore grouped daily data by month for this study. Thus, all subsequent analyses except for the spatial cluster analysis (i.e. Moran's I calculation) in this study were conducted with monthly temporal data resolution. That is, the dataset of norovirus outbreaks used for the analysis contained a total of 13,620 cases ($=5$ years $\times$ 12 months $\times$ 227 districts), of which 173 cases were positive (one or more outbreaks in a month). Note that the term "case" used in this manuscript is defined as the data corresponding to the information of occurrence or nonoccurrence in each month and each geographic region (administrative district). Throughout this manuscript, "positive case" and "negative case" indicate the months with and without occurrence of norovirus outbreaks, respectively, in a geographic region.

2.2. Environmental data and spatial analysis

Environmental variables potentially associated with the spatio-temporal patterns of norovirus outbreaks were selected according to the following criteria: 1) topographical characteristics including average slope and elevation that might be the natural environmental factors influencing norovirus transmission, 2) climate conditions potentially influencing the physiology or transmission of noroviruses in the environment, 3) demographic characteristics relevant to potential susceptibility or vulnerability of population to fecal contamination, 4) water and sanitation utilities that are potentially fecal sources or that provide environments favoring norovirus distribution, and 5) land-use patterns as syndromes of human activities that might be associated with the patterns of disease infection.