Mass Gatherings Health 5

Infectious disease surveillance and modelling across geographic frontiers and scientific specialties

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Infectious disease surveillance for mass gatherings (MGs) can be directed locally and globally; however, epidemic intelligence from these two levels is not well integrated. Modelling activities related to MGs have historically focused on crowd behaviours around MG focal points and their relation to the safety of attendees. The integration of developments in internet-based global infectious disease surveillance, transportation modelling of populations travelling to and from MGs, mobile phone technology for surveillance during MGs, metapopulation epidemic modelling, and crowd behaviour modelling is important for progress in MG health. Integration of surveillance across geographic frontiers and modelling across scientific specialties could produce the first real-time risk monitoring and assessment platform that could strengthen awareness of global infectious disease threats before, during, and immediately after MGs. An integrated platform of this kind could help identify infectious disease threats of international concern at the earliest stages possible; provide insights into which diseases are most likely to spread into the MG; help with anticipatory surveillance at the MG; enable mathematical modelling to predict the spread of infectious diseases to and from MGs; simulate the effect of public health interventions aimed at different local and global levels; serve as a foundation for scientific research and innovation in MG health; and strengthen engagement between the scientific community and stakeholders at local, national, and global levels.

Introduction

Throughout history, people have been congregating for social, religious, cultural, economic, political, and other reasons. However, as the world's 7 billion people increasingly travel across international borders, mass gatherings (MGs) of millions of individuals have become frequent events. Although these gatherings can confer tremendous benefits to mankind, they also increase risks to global health security[1] because travellers from a wide range of global locations can introduce infectious diseases into MGs that can then spread to other people in the local environment.[2–6] Conversely, travellers to MGs can be infected with diseases that are endemic in the local environment but not their home countries. Infected individuals—whether originating from the host country or elsewhere—can then transport locally acquired infectious diseases to their home environments, where they might then start new epidemics.[7–11]

Conceptually, MGs can be thought of as global-to-local-to-global events because they consist of a fairly symmetrical global-to-local convergence and subsequent local-to-global divergence of populations from around the world. As a result, infectious diseases can be detected and intercepted at several potential levels (figure 1). These include the attendees' home cities and countries, points of departure from and entry into the attendees' home countries, points of entry into and departure from the host country (eg, international airports), and the local environment of the MG. Since the host country is typically responsible for public health security for MGs, efforts to mitigate risks of infectious diseases tend to be most focused on the environment of the MG.[12–15]

Efforts to detect and respond to infectious disease events outside the host country, although important, have been hindered by an incomplete understanding of the potential relevance of these events to MGs and the complexities of international cooperation in confronting infectious disease threats of international concern.[16] However, scientific and technological advances in surveillance[17–21] and modelling[22–25] are creating new opportunities to strengthen awareness of the global threats of infectious diseases before, during, and after MGs. The synthesis of knowledge generated from traditional and novel surveillance systems for infectious diseases and integration of complementary modelling techniques[23,26–29] could form the basis for an enhanced risk monitoring and assessment platform that would provide valuable information to assist stakeholders of MGs with planning efforts. It would also generate public health intelligence that could be used to respond to emerging threats of infectious diseases in near real time. The momentum to make the most of these opportunities is increasing as stakeholders recognise the potential for infectious diseases to compromise the success of MGs.

Global-to-local surveillance

The complex and dynamic interactions of infectious agents between human and animal populations, their patterns of local and international spread, and the environment necessitate a timely and global approach to public health surveillance.[30,31] Currently, surveillance efforts to detect potential threats of infectious diseases during MGs predominantly focus on surveillance in the host city and country as a means to detect and swiftly deploy mass medical and public health responses, if needed.[12–15] In

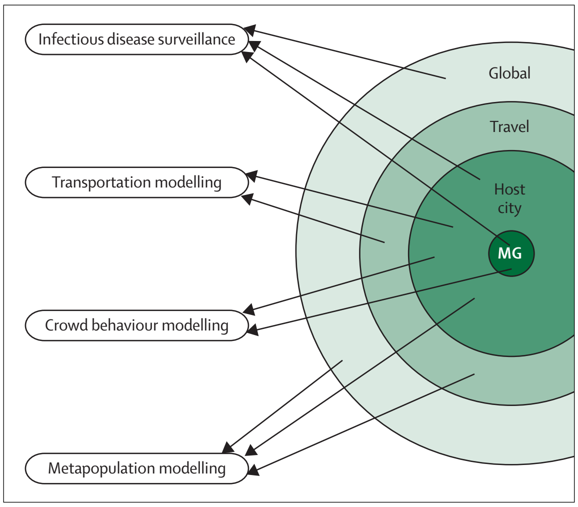

Figure 1: **Levels of disease surveillance and modelling opportunities at MGs**
MG=mass gathering.

developed countries that can effectively implement the novel approaches of indicator-based public health surveillance, clinically relevant and other complementary data sources are monitored for signals of disease outbreaks.[32] In developing countries in which public health infrastructure is often suboptimum, efforts are in progress to implement robust data gathering methods, enhance analysis capability, and improve capacity for electronic disease surveillance.[33] In either setting, hosting an MG creates a special opportunity to strengthen local public health surveillance and capacity and to develop novel solutions to mitigate risks of infectious diseases that create a lasting public health legacy.

For disease surveillance during MGs, efforts to harmonise local preparedness and response efforts with increased global awareness of infectious diseases are often constrained by the complexities of integration of real-time intelligence from global surveillance systems with information about global travel between sites of reported infectious disease outbreaks and the sites of MGs.[5,6] Despite the adoption of WHO's revised 2005 International Health Regulations,[16] difficulties in reporting processes and multilateral co-ordination present ongoing challenges. For example, governments perceiving economic or other risks might be reluctant to quickly and fully disclose information about risks of infectious diseases of international concern. Although formal reporting, surveillance, and response structures are essential, WHO, in conjunction with national public health organisations, has used informal surveillance for decades. Many important outbreaks were first identified through such sources, making event-based surveillance an important source of epidemic intelligence. Early indicators of emerging infectious diseases subsequently require verification by local health authorities.

The new generation of real-time technologies such as the Global Public Health Intelligence Network,[21] Program for Monitoring Emerging Diseases,[19,34–36] and HealthMap Project[17,18,37,38] use informal data sources from the internet to monitor disease activity. Online news outlets, health expert mailing lists, and millions of daily health-related queries in internet search engines offer free or low-cost sources of unstructured information, which when computationally filtered and mined can provide local and near real-time indications of potential or confirmed disease outbreaks. Together, these data sources could be used to overcome some of the limitations of traditional surveillance systems, including delays in reporting, inconsistent population coverage, and poor sensitivity for emerging diseases. As a result, they could be particularly insightful for areas of the world that have insufficient infrastructures for reporting public health information, but which are at increased risk of emerging diseases. These systems can complement traditional disease surveillance systems by allowing public health professionals to detect weak signals across borders and thereby create awareness at an early stage of emerging infectious disease risks that might affect MGs. So far, however, these systems remain weakly connected to local surveillance efforts, including those for MGs. International organising committees for MGs are well aware of these gaps in knowledge integration and are developing processes to bridge them before, during, and after MGs.

The scope of surveillance can be broadened by increasing communication between public health stakeholders and the public, including populations attending MGs who could report health-related matters. The rapid and widespread use of the internet and mobile phones in developed and developing countries has provided opportunities for crowdsourcing[39,40] through informal sources such as blogs, Twitter, and Facebook. Social media can function as a method of passive surveillance (eg, analysis of geographically tagged tweets) or assist with active surveillance (eg, public health outreach on Twitter for people reporting health events in the host city during an MG). Mobile phones, and particularly mobile internet use, can increase the availability of real-time information at any time and nearly anywhere in the world to the general public, public health practitioners, and clinicians.

Although internet-based informal data sources are increasingly essential for global surveillance of infectious diseases, important challenges remain.[30,31] Most notably the unavoidable drawbacks of these epidemic intelligence systems are the separation of the increasing background internet-generated noise from meaningful public health indicators, demands to verify indicators of potential public health significance, and opportunity costs of responding to false alarms. Preliminary evidence-based assessment, however, suggests that the aggregation of several data sources—so that assessments are not reliant on only one source of information—might attenuate this limitation by increasing their specificity. Furthermore, to achieve uniform and comprehensive global coverage, future developments of systems will need to address the digital divide, whereby places in the world that are the

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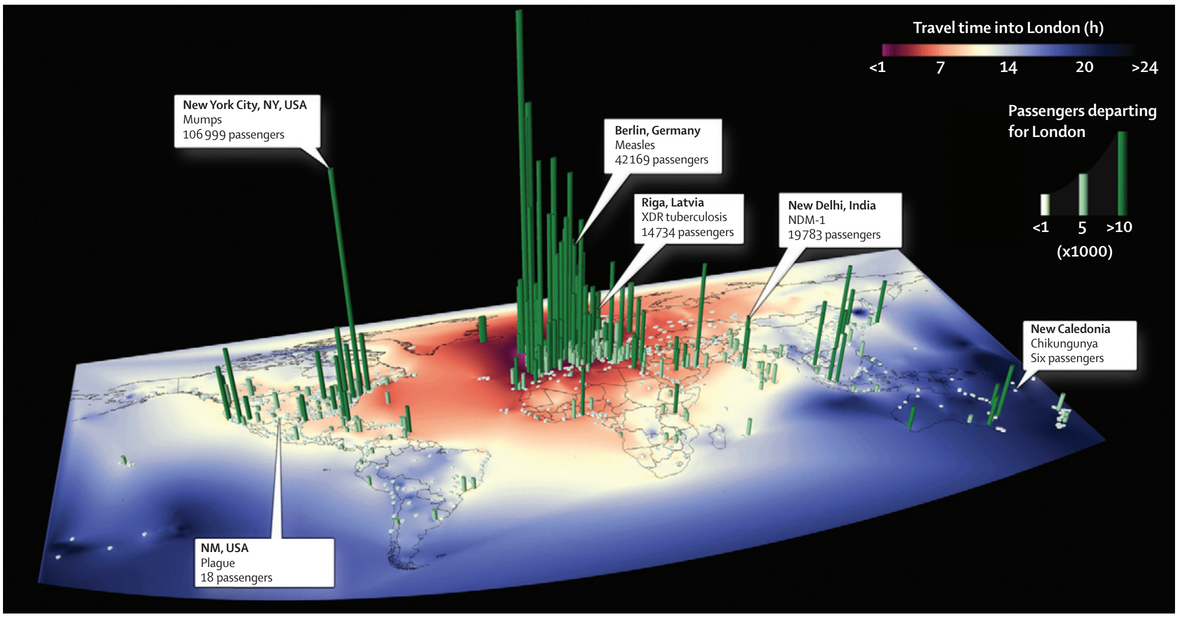

Figure 2: **Global patterns of international air traffic into London, UK, in July, 2009, and hypothetical infectious disease alerts from global surveillance systems**
Visualisations of international air traffic flows into London were derived from the analysis of worldwide passenger flight itinerary data for July, 2009. XDR=extensively drug resistant. NDM-1=New Delhi metallo-β-lactamase-1 enzyme (highly drug-resistant bacteria).

least technologically advanced also tend to have the greatest burden of infectious diseases. Although this new generation of innovative internet-based surveillance has the potential to overcome some of the limitations of traditional surveillance of MGs, the integration of novel and traditional approaches will provide the greatest usefulness for future surveillance of well established and newly emerging diseases.

Travel to and from MGs

The advent of commercial air travel in the 20th century fundamentally transformed the global movement of populations. Today, more than 2 billion people travel on commercial flights every year, creating unprecedented opportunities for locally emerging infectious diseases to quickly transform into international epidemics or pandemics.[41,42] This rapid increase and transformation in commercial air travel has also contributed to an increase in the overall number, frequency, and scale of international MGs. Although populations travelling to and from MGs might use different modes of transportation, commercial air travel remains the main mode of travel to and from MGs with a broad global representation of attendees. Since travel is a central feature of MGs, careful modelling of global movements of populations is essential to understand the potential implications of global outbreaks of infectious diseases near the time of MGs (figure 2).[5,6]

Infectious diseases can be introduced at MGs through one of several population groups—people directly participating (participants) in the event such as pilgrims at religious festivals, observing (observers) the MG such as spectators at sporting events, living (residents) in the host city or country who might interact with others at the MG such as food vendors, hotel staff, or event volunteers, and travelling to the MG host city for reasons unrelated to the MG (bystanders) but who might interact with others in the MG environment. Since the global origins, modes of travel, and infectious disease burden in each of these populations might differ greatly, independently understanding their travel movements is essential to assess public health risks. However, synthesis of the information needed to accomplish this task can be difficult because essential data tend to be stored in domains that are not linked (eg, host governments, international organising committees, and transportation industries). Since participants at some MGs must register to participate or seek a visa to attend, planners can have access to information about their geographical origins, although this information might have different levels of spatial resolution (eg, city level *vs* national level). Other complementary data sources (eg, ticket sales for sporting events) could provide additional insights into the local and global environments from which observers are originating. However, predictions of how residents might interact with other MG attendees can be difficult since some might be drawn to MG-related activities, whereas others might be motivated to stay away. Prediction of the global movements of bystanders to MGs is of public health importance because this population is typically very large and geographically diverse and hence could be an important source for the introduction of infectious diseases to the MG. Although modelling movements of travellers from their global origins to MGs is a challenging task, worldwide passenger-level flight data have been used to predict the numbers and global origins of individuals travelling to Vancouver, BC, Canada, before the commencement of the 2010 winter Olympic Games.[6] One of the limitations of this approach, however, is that prediction of global travel patterns to MGs that routinely change their location (eg, the Olympic Games and Fédération Internationale de Football Association World Cup) can be difficult because the past experiences of travel to MGs in different locations and seasons might not be readily transferrable to future MGs. Consideration of the season and timing of when MGs are scheduled to commence is important for the assessment of the public health risks because these are usually correlated with the numbers and global distribution of travellers to and from the city where the MG is hosted and might affect the infectious activity of pathogens with strong seasonal patterns due to the effects of climate, social, or other variables.[43–48]

In addition to commercial air travel, people will use other modes of travel to MGs. For example, during the annual Hajj pilgrimage about 20 000 pilgrims predominantly from Egypt and Sudan travel to Mecca through the Red Sea and an estimated 130 000 travel on land from countries sharing a border with Saudi Arabia.[5] The Kumbh Mela—a religious pilgrimage of Hindus along the river Ganges—is the largest MG ever recorded (an estimated 70 million pilgrims in 2007), but most of the participants travel from within India, and a large proportion of these travel using ground-based transportation. Hence, to the greatest extent possible, modelling travel patterns of people from all over the world converging at MGs should include the movements of individuals by land, sea, and air. Importantly, the predeparture health risks for each population, their accommodations after arrival into the host country, and how each population is likely to interact with others at the MG need to be considered separately. For example, during the G20 Summit, participants (political leaders and their entourages) would be expected to have low pretravel risks of infectious disease, reside in privileged environments where food or water-borne diseases are unlikely, and be highly sequestered from other populations at the MG. Conversely, for religious MGs such as the Kumbh Mela, pilgrims might have pre-existing health issues, be living in conditions in which the risks of acquiring food or water-borne diseases are increased, and have extensive interactions with other populations at the MG.

Integration of surveillance and modelling

Although surveillance and modelling of infectious diseases for MGs are targeted at different local and global levels, they are often not well integrated into one framework for risk monitoring and assessment and thus are restricted in their ability to generate useful public health intelligence in near real time. Although global surveillance of infectious diseases by use of traditional and internet-based methods generates news of hundreds of outbreaks worldwide on a daily basis, in some parts of the world this surveillance might lack sensitivity whereas in others the amount of information could overwhelm public health end-users who then struggle to understand the relevance of each outbreak to an MG. Quantitative analyses of global population travel patterns, however, can complement global epidemic intelligence by helping public health officials prioritise which outbreaks need their greatest attention. For infectious disease events occurring in places where few people are expected to travel to an MG, these events could simply be monitored. Whereas events of high public health importance (ie, involving highly virulent or contagious pathogens) and substantial population movements into an MG could lead to further action. Conversely, modelling-predicted numbers and geographical origins of global travellers to MGs before the start of the events could enable anticipatory disease surveillance in global locations where the largest population movements to the MG are expected. The principle of this bidirectional synergy between disease surveillance and transportation modelling was used in an analysis of the 2010 winter Olympic Games in Vancouver.[6]

Epidemic modelling is a powerful method that can be used to predict the spread of infectious diseases across space and time.[49] Metapopulation models have been used to simulate the movements of disease within networks, and the spread of infectious diseases through the global airline transportation network.[23,25,26] In these contemporary network models, nodes represent populations in and around cities with commercial airports and edges that connect nodes represent the numbers of travellers moving between cities across the network. Populations within each node are traditionally divided into compartments of individuals who are susceptible (S) to the infectious disease of interest, exposed (E, in mathematical models this term is usually synonymous with latent infection even though not all exposed individuals will develop latent infection), infected (I, in mathematical models this term usually refers to asymptomatic or symptomatic disease that might or might not be communicable), or removed (R, as a result of death, or natural or vaccinated immunity). During simulations that use these metapopulation S-E-I-R epidemic models, individuals in each compartment interact homogeneously with others in the same city but can also travel to or from all other cities across the network. Empirical data for travellers aboard commercial flights worldwide have been used in these models,[23,50] but data from other transportation networks (eg, sea-based travel) might also be relevant. For example, during the 2004 summer Olympic Games in Athens, Greece, thousands of international travellers were arriving everyday on dozens of large cruise ships. Yet to our knowledge, metapopulation models have never been adapted to the global-to-local-to-global features of MGs. Furthermore, these models have generally been used to simulate historical outbreaks or hypothetical what-if scenarios rather than actual outbreaks of infectious diseases as they arise. Thus, initial conditions in these models are typically defined (eg, population size of each

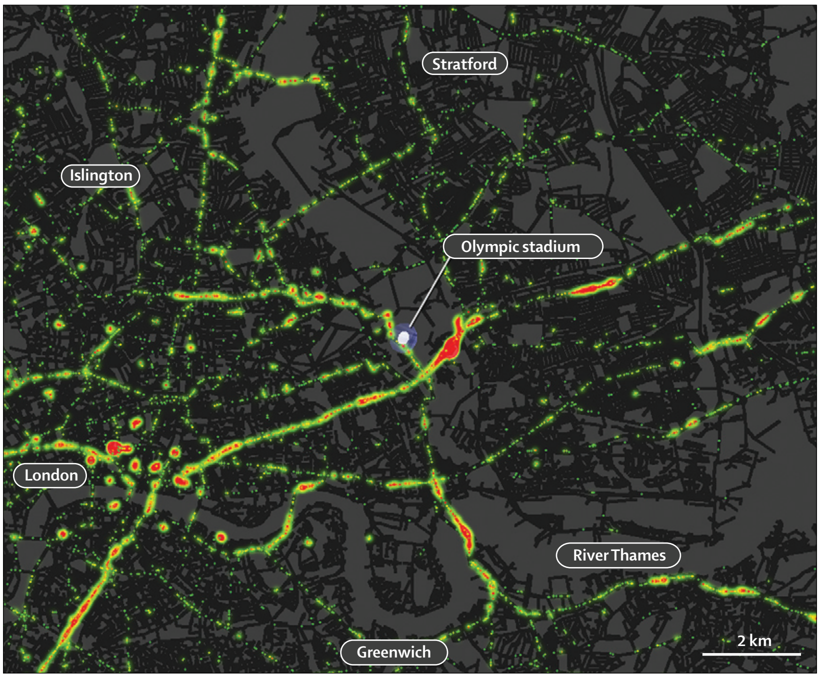

Figure 3: **Hypothetical traffic simulation around London, UK, using an optimum velocity model**
This hypothetical simulation shows that the population dynamics within a host city and around a focal point (eg, Olympic stadium) for a mass gathering can be modelled. Green areas depict free flowing movements of vehicular traffic, yellow areas vehicular traffic in moderate congestion, and red areas vehicular traffic in extreme congestion.

S-E-I-R compartment, reproduction number, and incubation period of the infectious agent) well before or after the onset of a real infectious disease outbreak. Generally, calculations are computed deterministically by use of differential equations or stochastically by use of Markov chains or related processes. Although model outputs represent the most likely realisation or distribution of realisations resulting from an outbreak of a particular infectious disease over a defined timeframe, simulations are not typically done iteratively with contemporary surveillance data that represent up-to-date, real-world conditions. Since the accuracy of model outputs is directly dependent on the precision of their inputs, the practical value of these models could be greatly enhanced if global epidemic intelligence generated from real-time surveillance systems was continuously reintegrated.

One of the most important assumptions in metapopulation epidemic models is that each individual in a node interacts in a homogeneous manner and hence has an equal probability of exposure to an infectious disease. Although this assumption can be a reasonable approximation for simulations in a large global network, it is likely to be inadequate for environments where MGs are being hosted.[28,51] In this context, greater spatial precision is needed to account for person-to-person interactions that could have a substantial public health effect both locally at the MG and across the global network. Modelling of crowd behaviour has long been used to simulate the movements of populations at MGs and thereby mitigate the risk of injury or death in these settings.[29,52,53] These models differ greatly from metapopulation models in that they incorporate much greater spatial detail, including individual pedestrians or small groups and information about the environment such as buildings, roads, and local transportation systems (figure 3). The factors considered in models of crowd behaviour are that the movements of attendees at MGs tend to be affected by the same exogenous forces, so clustering of individuals in space and time is expected; might be affected by social interactions and herding effects, which are important determinants of clustering in space and time; and typically lead to congregation and therefore crowding around one or a few focal points. Results from studies of recurring MGs have shown that the behaviours of attendees follow very similar patterns from one MG to the next.[5] Since a central objective of crowd behaviour models is to safely distribute population density across space and time, they might also be effective at attenuating the risks of person-to-person transmission of communicable diseases at MGs. As a result, the integration of these two types of models into a multiscale framework (in which global metapopulation model outputs are coupled with local crowd behaviour model inputs in the lead up to an MG and vice versa once the MG has concluded) could become an important foundation for simulations of risks of infectious diseases at MGs. In addition to modelling the expected movements of people and infectious diseases, an integrated global-to-local-to-global simulation framework could be used to assess the potential public health effect of interventions that are intended to disrupt, delay, or even prevent the spread of infectious diseases. The metapopulation part of an integrated model could be used to assess the effect of interventions targeted at the global source of an emerging epidemic (eg, vaccination of susceptible individuals, post-exposure prophylaxis for those exposed, and treatment of infected individuals) and at international points of departure and arrival (eg, screening travellers for signs and symptoms of infectious diseases as they depart from or arrive at international airports). The crowd behaviour part could be used to assess the potential effect of local interventions aimed at mitigating the attendees' risks of exposure to infectious disease (eg, promotion of good respiratory hygiene by coughing or sneezing into a sleeve), improving hand hygiene, or controversial infection control measures such as wearing face masks or social distancing in an increased risk setting (eg, MG during an international epidemic or pandemic).

Case studies

2009 Hajj and influenza A H1N1 pandemic

The emergence of the influenza A H1N1 pandemic in the spring of 2009 caused concern among countries that were scheduled to host MGs.[54] After the H1N1 outbreak was officially declared a pandemic,[55] the annual Hajj to Saudi Arabia was the first main MG that was scheduled. The Hajj is the largest annual MG in the world with an estimated 3 million pilgrims from more than

183 countries.[56–58] It is different from many other MGs because the attendees tend to be older in age, speak a huge range of languages, come from different cultural backgrounds, and might have underlying health issues that make them particularly susceptible to non-infectious and infectious diseases. As a result of the intrinsic delays in the production of an influenza vaccine for the pandemic, only a few developed countries were able to vaccinate pilgrims against H1N1 with sufficient lead time for them to develop immunity before the start of the Hajj.[5] Of particular concern was that pandemic influenza would be drawn into the Hajj by travelling pilgrims, where it would then locally propagate before being transported back to cities and countries around the world. Because of concerns that MGs during an influenza pandemic could amplify and accelerate the global spread of the infection, Saudi Arabia convened a meeting with national and international public health organisations in June, 2009, to consider the most effective and efficient countermeasures to mitigate the effect of pandemic influenza on pilgrims, the countries from which they came, and the global community. One of several recommendations from this meeting[59] was to strengthen the gathering and communication of public health surveillance data within Saudi Arabia, which until then had largely relied on a paper-based reporting system.

Communication of public health intelligence during MGs is a challenge because of the large numbers of attendees, rapid, large-scale movements of people, and fairly short stay by attendees.[14,15,60–70] Advances in information technology, however, have enabled the gathering and wireless transmission of text-based or form-based data by use of mobile phones and smart phones. Mobile phones can be used to easily communicate data to web-based servers through short-messaging services. Smart phones enable much greater flexibility, can support adaptive data gathering, have global positioning systems that can geographically tag data inputs, and have a video function.[71] More than 90% of the population worldwide are covered by mobile phone networks and more than 140 countries provide third-generation wireless telecommunication services,[72] therefore mobile-phone-based data gathering has become an increasingly valuable method for public health surveillance.[73,74] Data gathering by use of these readily accessible handheld devices has been shown to be efficient by decreasing data entry time and reducing costs, which is why many end-users prefer data entry through mobile phones to paper-based reporting methods.[75] Furthermore, these devices also have the potential for bidirectional communication so that public health messages could be directed to attendees at MGs.

On the basis of its potential to strengthen health surveillance, in 2009 the Saudi Government conceived, developed, and deployed the first ever mobile-phone-based platform to rapidly generate and communicate public health intelligence during the Hajj (figure 4). This proof-of-principle initiative was undertaken to assist the early detection of emerging outbreaks of infectious diseases at the Hajj, improve the efficiency of case reporting by communication of information in real time to a central emergency operations centre, and aid operational effectiveness by production of meaningful visualisations of data and statistical and spatial analyses through the use of geographically tagged data. During this project, nine infectious diseases were monitored—pandemic influenza A H1N1, influenza-like illness, meningococcal meningitis, viral haemorrhagic fever, plague, yellow fever, cholera, food-borne illness, and poliomyelitis. Questionnaires about these diseases were designed, uploaded to a central server, and then wirelessly disseminated to laptops and smart phones in Saudi Arabia at points of data gathering. During deployment, field investigators who were assigned to strategically established local clinics and hospitals in and around Mecca identified 73 cases of influenza A H1N1 and two suspected cases of dengue haemorrhagic fever. Information gathered from the field was quickly analysed and synthesised by epidemiologists and then presented to public health decision makers in the form of daily reports.

Some of the important lessons that were learnt from the deployment of a mobile-phone-based surveillance system during a large-scale MG while there was an infectious disease pandemic were that mobile-phone technology could be swiftly integrated into the existing information technology infrastructure of Saudi Arabia's Ministry of Health, provide greater opportunities for public health officials in the field to gather information electronically at the point of contact with pilgrims, enable efficient gathering and real-time transfer of information to a centralised emergency-operations centre, and form the basis of an integrated platform to ease synthesis of epidemiological, clinical, and laboratory information to generate public health intelligence for decision makers.

2012 summer Olympic Games

The opening ceremonies for the 30th summer Olympic Games are scheduled for July 27, 2012, in London, UK, one of the world's most centrally located cities. In

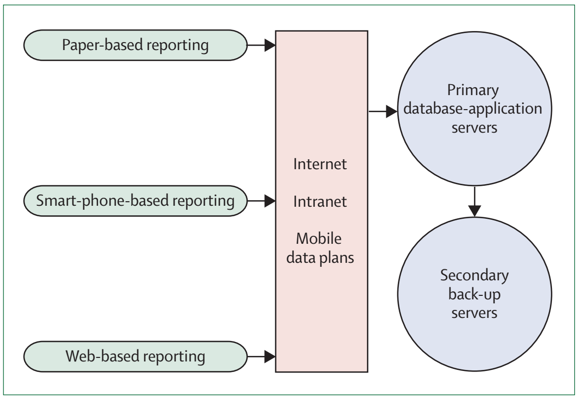

Figure 4: **Information technology used for public health surveillance during the 2009 Hajj, Mecca, Saudi Arabia**

preparation for this event, the Health Protection Agency has initiated a dedicated, multidisciplinary strategic risk assessment process aimed at monitoring national and international health risks. To complement this process, we did a conceptual analysis, integrating global airline transportation modelling of populations travelling to London at the time of year when the Olympic Games are scheduled with global epidemic intelligence from infectious disease surveillance systems (figure 2). We considered four population subgroups—participants, observers, residents, and bystanders. Although accurate modelling of the predicted movements of participants and observers was not feasible at the time of writing this review, forthcoming data for numbers of competing athletes, their countries of origin, the expected sizes of their entourages, and worldwide ticket sales for the Olympic Games might provide valuable insights into the expected movements of these populations. By analysing past worldwide flight itinerary data from the International Air Transport Association for July during 2007–09, we noted that the global distribution of travellers flying into London in July was highly consistent for these 3 years. Furthermore, temporal analyses of the flows of international travellers at London's five major airports (Heathrow, Gatwick, Stansted, Luton, and London) showed that yearly flows typically peak in July, coinciding precisely with the onset of the summer Olympic Games (webappendix). If these trends are repeated, then London would receive an estimated 2·5 million additional travellers in July relative to February, when traveller flows are typically at their nadir. This estimation, however, does not account for the possibility that bystanders or local residents might modify their travel plans to or around London because of the Olympic Games. To assess the effect of the summer Olympic Games on global travel behaviours, we analysed international air traffic data in each of the three previous host cities and noted that flows of travellers were highly variable. Using an autoregressive integrated moving average model in which the changing baseline trends in air travel were controlled for, we noted a substantial surge in the numbers of travellers at the time of the Sydney Olympic Games in 2000, not much change in numbers in Athens in 2004, and a slight reduction in Beijing in 2008 (analyses not shown). We included hypothetical alerts of infectious diseases to show that some events would be of low public health relevance to the London Olympic Games because of the small risk of disease translocation (eg, plague in New Mexico, USA, and chikungunya in New Caledonia), whereas other events might need greater attention from public health officials (eg, mumps in New York, NY, USA, and measles in Berlin, Germany). The described modelling activities will inform London's planning for the Olympic Games and complement disease surveillance systems in the UK. In 2012, international public health events will be closely monitored in London by the Health Protection Agency (in association with WHO) to ensure that the implications of any event are properly understood and appropriate actions are taken; the data relating to international travellers and transportation modelling analyses will help with the interpretation of the importance of global infectious disease events.

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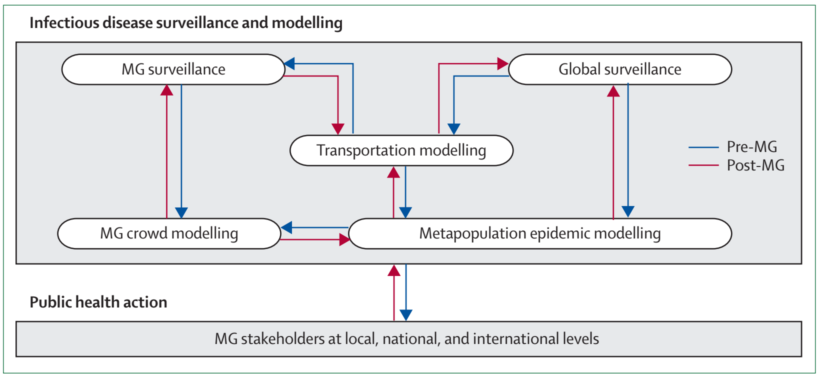

Figure 5: **Proposed integrated framework for an enhanced global-to-local-to-global risk monitoring and risk assessment platform for MGs**

The proposed framework represents the integration of several surveillance and modelling activities before, during, and immediately after an MG. Global surveillance of infectious diseases could be coupled with transportation modelling of populations travelling to an MG and this could help with anticipatory surveillance at the event. By integrating epidemic intelligence from global surveillance systems with global transportation analyses, metapopulation models could simulate the spread of disease across space and time and be used to measure the expected public health effect of interventions at different global-to-local levels. Outputs from metapopulation models could become inputs for models of crowd behaviour at the onset of an MG, whereas outputs from models of crowd behaviour could become inputs for metapopulation models at the conclusion of an MG. MG=mass gathering.

The future

The contemporary rate of growth of the global population with the rapid development in mobility through commercial air travel is increasing the number, frequency, and scale of MGs. Previously unrecognised infectious diseases are emerging faster than ever before whereas many previously controlled diseases are re-emerging.[76,77] Opportunities for these two products of globalisation to interact are increasing with potentially serious implications to health, security, and economic activity worldwide.[42] Although the scientific and technological components and data sources needed to generate real-time intelligence that could mitigate risks of infectious diseases during MGs exist, their integration is suboptimum. Further research and development to build bridges across traditionally isolated but complementary scientific specialties, efforts to embed this collective knowledge within existing and emerging technologies, and endeavours to integrate disparate sources of data while acknowledging and addressing legitimate concerns about data sensitivity and privacy would represent substantial advances in the emerging specialty of MG health (figure 5). However, local and international stakeholders must collectively promote and foster a culture of cooperation, while ensuring that sufficient time and financial resources are available to plan and implement effective, innovative public health measures. Furthermore, the early and continued engagement of

Search strategy and selection criteria

We identified references for this Review by searching Medline for articles published in English from January, 1948, to June, 2011, by use of the search terms "mass gathering", "disease", "outbreak", "surveillance", "modelling", "public health", "prevention", and "travel". We reviewed the articles found during these searches and relevant references cited in the articles.

planners, health officials in the host city and country, and international public health organisations will be essential to ensure that new knowledge can be effectively converted into real benefits for both local and global public health security. For cities and countries hosting MGs, opportunities to strengthen risk assessment and risk mitigation capabilities through the novel integration of multidisciplinary scientific methods and multiagency public health practices would form the basis not only for a lasting domestic public health legacy, but also a repository of new knowledge that would benefit the hosts of future MGs worldwide.

Contributors

KK wrote the initial and final versions of the review with input from the authors who prepared drafts for specific sections. SJNM and ZAM together wrote the section about mobile-phone-enhanced public health surveillance during the 2009 Hajj. RE and JS undertook and synthesised the literature review about surveillance and modelling activities during MGs. WH, DK, and KK jointly undertook and visualised the transportation analyses pertaining to the 2012 summer Olympic Games in London, UK. JA wrote the section about metapopulations and epidemic modelling. AJ wrote the section about crowd behaviour modelling and produced a hypothetical traffic simulation in London. MB, BM, BH, and MC rigorously reviewed and made substantial edits to the review. JSB led the section about global-to-local infectious disease surveillance. All authors subsequently edited the review before its completion.

Conflicts of interest

KK owns intellectual property in technology related to global air travel and infectious diseases. The other authors declare that they have no conflicts of interest.

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