Abstract  Background  Epidemics can be represented mathematically using a variety of models. One of these, the Kermack-McKendrick model, has been used to support health policy decisions concerning vaccination requirements. An unrelated body of literature suggests that some behaviours, including some types of violence, may spread in ways analogous to the contagious spread of infectious diseases, a process that has been characterized as “behavioural contagion”.  Methods  Various parameter values reflecting the characteristics of crowds were substituted into the Kermack-McKendrick model. Computer simulations were used to evaluate the impact of these parameter values.  Results  The simulations reproduced several features of crowd violence: the tendency for riots to occur in large groups, the importance of rapid removal of violent individuals from crowds, and the roles of alcohol consumption and social identification processes.  Conclusions  Epidemic models may be of relevance to the prevention and control of violent behaviour as they can assist with the identification of high-risk situations and prevention strategies. Theoretical constructs related to epidemic theory may have broad applicability for modelling the unstable course of some mental disorders.

Introduction  Diseases may be categorized as endemic or epidemic. Endemic describes the occurrence of a disease within a population at its expected or baseline rate, whereas an epidemic disease is one occurring with a frequency greater than normal expectancy [1]. In epidemiological theory, endemic diseases and epidemic diseases are addressed differently.

An endemic disease is characterized by a stable baseline frequency (e.g. incidence or prevalence), and these population proportions can be estimated using a probability sample drawn from the population. Similarly, in analytical research, the frequency of disease can be related to various potential determinants in order to evaluate etiological hypotheses. Generally, in chronic disease epidemiology, the population frequency is regarded as being fixed, such that the challenges involved in estimating the relevant frequencies are those of statistical inference. Statistical methods are used to quantify the impact of random error resulting from sampling variability. The concepts underlying statistical analysis have their mathematical foundations in the “law of large numbers”, sometimes attributed to Jacob Bernoulli [1]. Statistical estimates become more stable as sample sizes increase, such that stable estimates arise out of random samples. Epidemiology, especially as it is applied to endemic chronic diseases, is, therefore, largely oriented towards concepts of stability in estimation and inference.

In epidemic diseases, a different set of methodologies are required. Here, there is no stable underlying probability or frequency to be estimated. Rather, the frequency of the disease is unstable and the behaviour of epidemic disease is guided by the “mass action principle” [1] whereby the number of future cases is regarded as a function of the number of current cases and the number susceptible to the infection in the population.
Mathematical models of epidemic diseases

A commonly employed mathematical framework for modelling epidemic diseases is the Kermack-McKendrick model [2]. The simplest expression of this model divides the population into three categories: susceptible, infective and recovered. The model can be evaluated in a series of stages (see equations 1–3, below) or can take the form of a set of differential equations which can be solved using numerical methods. In either case, the population is assumed to be freely mixing such that there is some chance of contact between any two population members at each stage. At each contact, there is also some probability of transmission. However, this probability applies only to contacts between infectives and susceptibles, the recovered members of the population have immunity and are, therefore, no longer susceptible.

The Kermack-McKendrick model [3] can be evaluated as follows:

1. \[ x_{n+1} = (1–p)\alpha_n x_n \]
2. \[ y_{n+1} = (1–e^{-\alpha n})x_n + b y_n \]
3. \[ z_{n+1} = z_n + (1–b)y_n \]

where \( x = \) susceptible, \( y = \) infective and \( z = \) removed, \( a = –\ln (1–p) \) where \( p \) is the probability of transmission and \( b \) is the proportion of infectives remaining infective at the end of the interval, the subscript \( n \) indicates the numbers within the three groups at a particular stage and \( n + 1 \) represents the number in a group at the next stage.

An interesting feature of the Kermack-McKendrick model is that, depending on the probabilities employed and the proportions of the population in the various groups, divergent predictions emerge. Under some circumstances, the probability of being in the infective group will decline, whereas in slightly different circumstances it may increase rapidly. Fig. 1 presents simulations with different parameters. When the simulations start with 500 susceptibles, one infective and no removals and with parameters \( p = 0.001 \) and \( b = 0.3 \), no epidemic occurs. However, increasing the size of the population (e.g., starting with 1000 susceptibles and one infective) or increasing \( p \) or \( b \) results in the occurrence of an epidemic. The underlying principle is that whenever the various parameters combine to produce a situation where an infective person infects, on average, more than one person during the course of their infectivity, then an epidemic is predicted to occur. Because each of the new infectives can infect susceptibles, the dynamics include a positive feedback mechanism, creating the unstable dynamics depicted in Fig. 1.

Behavioural contagion and crowd violence

While the Kermack-McKendrick model was developed in order to assist with an understanding of infectious diseases, the model itself is more closely aligned to the idea of contagion than with microbial pathology per se. Any factor, including a behaviour that can be transmitted from one person to another, could lead to similar unstable epidemiological behaviour. In fact, there is a large literature concerned with the occurrence of behavioural contagion related to mental health. According to a 1998 review, violence comprised one of six categories of situations in which behavioural contagion may occur [4], the others being: hysterical contagion, rule violation behaviour, deliberate self-harm, financial behaviour and consumer behaviour. Some contagious behaviours have been observed to occur in situations of higher density and in larger groups, consistent with the behaviour of infectious epidemics [5]. Nail and Helton [6] regarded behavioural contagion as one form of social influence, differentiating it from compliance conformity.

A specific role for contagion in the spread of crowd violence remains speculative, although one formal analysis of aggressive behaviour in a children’s day care centre did identify statistically significant contagion [7]. However, predictions of the Kermack-McKendrick model do seem consistent with factors that are thought to contribute to the risk of outbreaks of crowd violence, particularly in circumstances where the violence is difficult to understand in other terms. These factors have been discussed in more detail in a previous paper [8]. For example, factors that increase the transmissibility of such behaviours would be expected to contribute to the occurrence of riots: factors that increase social identification, for example (wearing team colours, being of similar age, collective behaviours such as chanting or singing). The probability of transmission may be increased by alcohol, which has disinhibiting properties, and by increased emotional arousal. Finally, the duration of time for which a violent individual remains in a crowd (prior to removal, in this case not by the development of immunity, but by police or bystander intervention) would be predicted to influence the probability of
transmission of the behaviour to other crowd-members who are vulnerable to its transmission.

In general, the crowd-control techniques that are commonly applied in an effort to prevent or avert violence are consistent with the idea of a contagious dynamic. For example, stadiums and other sporting venues attempt to channel spectators in such a way that they do not mix in a chaotic fashion. Crowd-control principles focus on rapid identification of problematic behaviours, and rapid removal of disruptive individuals from the crowd.

These principles make it much easier to understand the otherwise puzzling occurrence of apparently pointless and inexplicable violence after sporting events in North America. In Europe, where there has been much concern surrounding hooliganism at football games, the violence has tended to adopt a dynamic characterized by altered social forces, leading to the expression of conflict between supporters of rival teams or groups with different, e.g. national, allegiances. The pattern in North America has often been impossible to describe in these terms and has often seemed quite inexplicable, for example, the occurrence of violent riots in home cities after sports victories. However, given the possibility of behavioural contagion and the dynamic predictions of the Kermack-McKendrick model, it is explicable as a contagious behaviour.

### Dynamic models and mental health and illness

A key difference between a model such as the Kermack-McKendrick model and the statistical models more commonly employed in chronic disease epidemiology (e.g. logistic regression models) is the dynamic behaviour of the former type of model. A logistic regression model, as with other statistical models, is concerned with estimating proportions (more precisely, log odds in this case) that will be interpreted as probabilities or risks in relation to predictive variables. Such models are very useful for describing the frequency of a disease in relation to its determinants, and are thereby of key value for epidemiological research. However, in dynamic outcomes where there is no "steady state" frequency, but where there rather exists the possibility of dramatic fluctuation, models such as the Kermack-McKendrick model are more applicable. The key feature of the model is the possibility, inherent in the model equations, either of negative feedback (i.e. a lower frequency of the disease or behaviour leading to the propagation of fewer new cases) or of positive feedback (i.e. situations in which increasing numbers of cases lead to even more cases developing). This basic principle of an unstable equilibrium within a system may have important implications for mental illness generally. In mood disorders, for example, cognitive and behavioural models predict the possibility of positive feedback, potentially leading to "catastrophic" outcomes. One model of mood disorder dynamics drawing upon these principles has been described [9]. Increased levels of depression, for example, may lead to more negative thinking and a reduced level of participation in pleasant or rewarding activity. These factors, in turn, may feed back to increase the level of depression [10]. Traditionally, epidemiologists have concerned themselves primarily with stable frequencies in populations, but it is interesting that some aspects of epidemiological theory may actually help us to understand the dynamics of unstable mental health *within* individuals.

### Conclusions

The theme of the 2003 meeting of the World Psychiatric Association Section of Epidemiology and Public Health was the role of theory in psychiatric epidemiological research. Generally, theory in psychiatric epidemiology is taken to mean that deriving from the social sciences. It is interesting that an aspect of epidemiological theory, epidemic theory, may have applicability in understanding certain events that might otherwise be difficult to explain (such as otherwise inexplicable outbreaks of crowd violence).

There is an extensive social sciences literature about the emergence of crowd violence. The historical evolution of theories about crowd violence was reviewed by Reicher who, within the context of the St. Paul's riot in Bristol, favoured a social identity model over previous models. This model posited that crowd members elaborate a situational social identity which provides them with a guide to action and conforms to their social identification [11]. Reicher argued that the social identity model represented an advance over previous theories because it was able to explain the limits of crowd violence, specifically, that expression of violent behaviour would only be facilitated in situations where it was consistent with emergent social norms within the crowd. However, these views do not oppose the use of the concept of contagion. In fact, Reicher explicitly invoked contagion in his description of the social identity model, proposing that the emergent social norms are established within a crowd largely by observation of the behaviour of others and within the context of social identification. Thus, newly emergent social norms may affect the 'p' parameter in the Kermack-McKendrick model, with a potential either to facilitate or impede the contagious spread of violent behaviour.

Recommendations for the prevention of crowd violence generally mirror the strategies employed in the containment of infectious diseases, especially the need for rapid isolation of violent individuals [12]. Two other recommendations [12] are predicted directly from the Kermack-McKendrick model: the need to reduce access to disinhibiting substances, especially alcohol (which would increase 'p'), and the need to disperse large groups (reducing the number of susceptibles below a threshold level).

Infectious disease models and concepts were recently
applied, using a narrative format, to post-traumatic stress disorder [13]. Also a meta-analytic review has summarized evidence for the contagion of depressive symptoms and mood, reporting that it was both strong and consistent [14]. These findings present a hypothesis that contagion may be a more widespread and important phenomenon than usually assumed. Finally, a general feature of this branch of epidemiological theory – the emergence of positive feedback in certain situations – may help to understand some of the unstable aspects of mental illness in general.

References
