PART 1   HEALTH AND DISEASE

Chapter 1

The transmission and prevention of infectious disease

CHRISTON J. HURST and
PATRICIA A. MURPHY

Introduction

The purposes of this chapter are threefold. First, it introduces the subject of modeling the epidemic versus endemic propagation of infectious disease through populations of individuals, for which a compartmental modeling approach is used, and the mathematical products are formally known as 'disease transmission models'. Second, it explains the routes by which the causative microbial agents are transferred between individuals who comprise the population. Third, it describes the use of disinfection to prevent or control the occurrence of those human diseases that are caused by pathogenic microorganisms. Other disease prevention measures are also mentioned. These other measures include physical barrier concepts, immunization and the use of antibiotics. Finally, the effectiveness of utilizing disease prevention measures is presented both by examining historical data for human death rates due to endemic typhoid fever in the United States during the early 20th century, and by using a mathematical model developed for epidemic disease.

Terminology

Pathogenic organisms are termed 'infectious agents' for epidemiological purposes, and this sets them apart from other causes of disease such as exposure to chemical agents. There are three basic considerations involved in the cycle of infectious disease transmission. First, there must be a source or reservoir of the infectious agent and the agent must escape from that reservoir. The source may be a human, some other animal, or the environment. Second, the agent must be conveyed to a susceptible host by some path or route. Third, there must be a susceptible host, and unless the causative microorganism produces only skin surface infections, the agent must successfully gain access to the interior of the host's body through some

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portal of entry. Portals of entry are the openings by which the organism gets past the barrier posed by intact skin. Common portals of entry include the respiratory tract, the gastrointestinal tract, the genitourinary tract, the eye, the ear and wounds to the skin such as tears, abrasions, burns and punctures (Isenberg & D'Amato, 1991). Absence of any one of these three considerations – existence of a reservoir, means of conveyance and availability of a susceptible new host – precludes disease transmission. Thus, all three considerations present opportunities to prevent the occurrence of infection, and this knowledge allows us to identify places in the cycle of disease transmission where specific measures (e.g. disinfection) can be used to interrupt the cycle.

It may be helpful to discuss and classify infectious agents by their mode of transmission, because the mode of transmission influences our choice of methods for disease control. Epidemiologists have tended to discuss the diseases transmitted between humans as being either 'direct' or 'indirect'. This classification possibly represents a misnomer, but the following is an attempt to explain the dichotomy. The term 'direct' transmission is used to indicate that the pathogens are passed either by direct physical contact between the human reservoir and the new host, or through an environmental route that is very short in terms of travel time and distance, such as coughing or sneezing directly onto someone. In these instances, our preventative efforts are directed toward the source of the disease. 'Indirect' transmission refers to those diseases for which the causative agent is carried to a susceptible host by an insect vector (vectorborne), an aerosol (airborne), solid environmental surfaces termed fomites, food, or water (all the last three described as vehicleborne). If transmission is 'indirect', then our preventive efforts are aimed toward various points along the environmental route.

Alternatively, the routes by which infectious microorganisms are transferred from one individual to another can be divided into those whose transmission relies upon direct physical contact versus those for which the transmission has some environmental component. Only a relative minority of diseases result from infectious agents that are transferred by direct physical contact between individuals. The majority of infectious agents are instead transmitted by indirect contact, meaning that the infectious agent moves through the environment for at least a short time or distance before it encounters a new host. This latter category therefore includes all of the 'indirectly' transmitted diseases plus the majority of 'directly' transmitted diseases. The exposure of the infectious agents to the environment can be viewed as beneficial, as it often allows us to use disinfection as a means of preventing transferral of the agents. This chapter employs the alternative approach to classifying disease transmission routes, i.e. direct physical contact versus environmental.

Two additional concepts need to be mentioned before delving further

into this chapter. The first concept is that of primary versus secondary transmission. Primary transmission is the initial introduction of an infectious agent into a group of susceptible individuals. Secondary transmission is the subsequent transfer of the infectious agent from the initially infected individuals to other members of the group. Primary and secondary transmission of a disease can occur by different routes. An example used later in this chapter is the disease typhoid, which often has water as the vehicle of primary transmission into a population, and for which food contaminated by handlers may then serve as a vehicle of secondary transmission within the population. The second concept is prevention of disease, which is the hallmark of public health. Disease prevention can be divided into three separate phases, termed primary, secondary and tertiary. Primary prevention is preclusion of disease either by reducing the exposure of new susceptible 'host' individuals to the disease agent, or by altering the susceptibility of the host. Secondary prevention consists of early detection of the disease which hopefully leads to successful early treatment. Tertiary prevention consists of treatments intended to alleviate disability resulting from the disease and attempts to restore effective functioning of the individual.

Modeling the transmission of disease through populations: epidemic versus endemic

Modeling the transmission of infectious disease through populations of animals and humans has been explored by a number of researchers. Figure 1.1 presents a very basic example of the models developed for these applications. Such models are commonly refered to as 'Disease transmission models', and represent a type of compartmental model. In Figure 1.1 the individual compartments are shown as boxes representing segments of the population being studied. The different compartments are connected by solid arrows that represent the directions in which individual members of the population move from one compartment to another. This movement is expressed in the form of daily rates of movement, which are sometimes described as the 'force' of flow through the model. The model presented in Figure 1.1 has four compartments: susceptible (those individuals who are susceptible to infection by the pathogenic microorganism whose affect is being studied); infectious (those individuals who have become infected and are in a state where they can transmit the infectious agent to other individuals); immune (those individuals who have successfully completed convalescence from the infection and who are, for at least a time, resistant to reinfection); and removed (individuals who at least temporarily are excluded from the population under study). In this example, the removed individuals are those who have died from the infection. Figure 1.1 also shows the point in the model at which transferral of an infectious agent
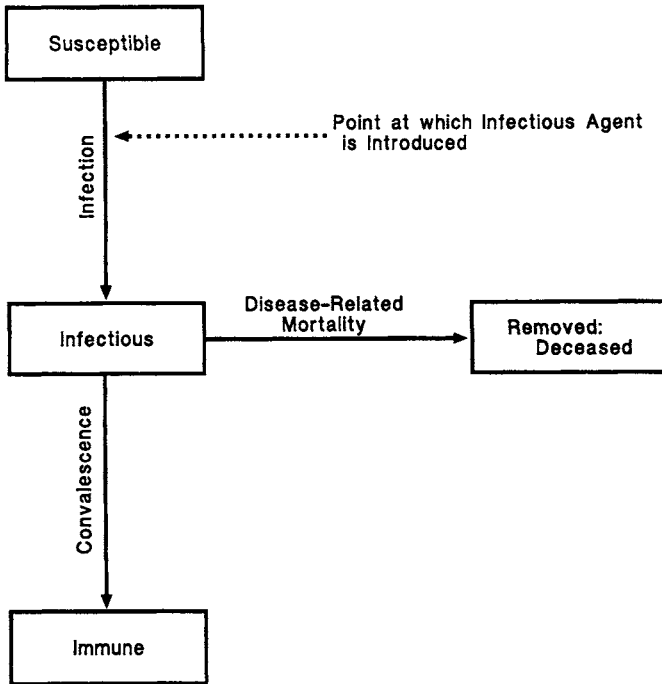
Figure 1.1   Basic compartment model appropriate for describing the epidemic propagation of disease through a population and the response of individuals to that disease. Models of this type are commonly termed 'disease transmission models'. This model also shows the point at which an infectious agent (causative microorganism) is transmitted to susceptible individuals.

occurs, represented as an arrow with a dotted line. For ease of comparison, all of the disease transmission models presented in this chapter will be drawn with a common format. Those boxes representing 'included' individuals will be listed vertically, with the box representing the immune individuals at the bottom. Boxes representing 'removed' individuals will be separated horizontally either to the right or to the left of those boxes which represent 'included' individuals.

The model presented in Figure 1.1 was developed for epidemic disease transmission, and accordingly contains relatively few compartments. Figure 1.2 presents a model developed for endemic disease transmission. This takes us a large step forward to a model that is more complex and more complete. In Figure 1.2, individuals can move in and out of three removed categories: susceptible, infectious and immune. The epidemic disease model presented in Figure 1.1 allows for disease-related mortality. The endemic disease model shown in Figure 1.2 likewise includes disease-related mortality, and additionally allows for both natural mortality and

vaccine-related mortality. The model shown in Figure 1.2 also enables the addition of susceptible individuals to the population through new births, and returns immune individuals to the susceptible compartment through the eventual waning of immunity.

It is clear that models for disease transmission can grow very complex. Black & Singer (1987) have discussed the relative merits of elaboration versus simplification in mathematical disease transmission models, and concluded that extensive elaboration is not always necessary. Disease transmission models found in the literature can vary with respect to both the compartments they contain and the indicated movement of individuals. Such variation reflects the intended application of a given model, i.e. whether it is for endemic versus epidemic disease, and whether it represents a disease exposure which is pertinent to only a subset of the population, such as infants, or to the entire population.

Figure 1.3 represents an epidemic disease transmission model drawn for this chapter to illustrate a series of equations published by Anderson & May (1985), who developed the equations through observation of human populations. This model differs in three ways from what is presented in Figure 1.1. First, the model shown in Figure 1.3 includes a compartment for infants who are temporarily protected from infection because of maternal antibodies. These maternal antibodies can be acquired either through the
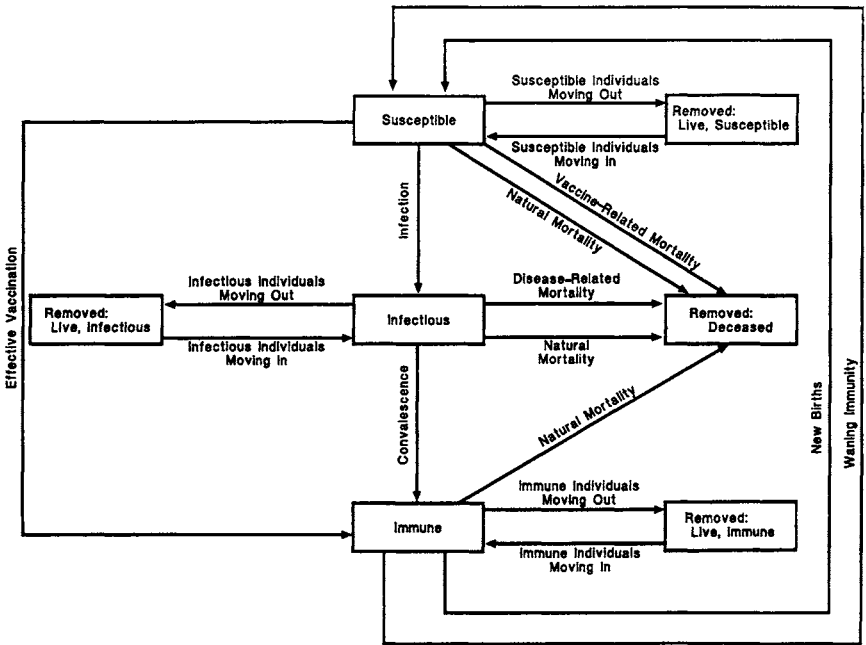

Figure 1.2   Compartment model appropriate for describing endemic disease propagation in a dynamic population.
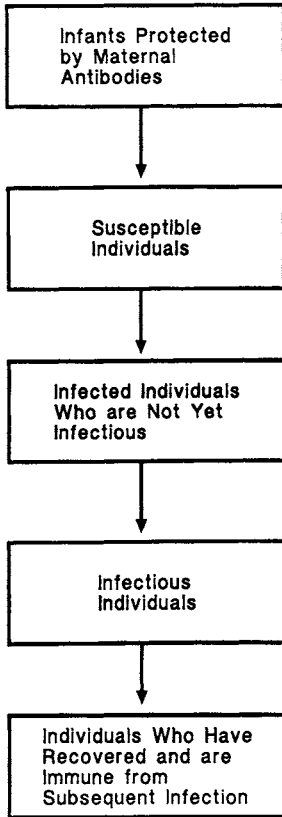
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Figure 1.3   Compartment model for epidemic transmission of disease
in a human population, including compartments for both infants not yet
susceptible to infection, due to protection by maternal antibodies, and
individuals who are in an incubation period following infection but prior
to development of a state of infectiousness. This figure has been drawn
to illustrate equations presented by Anderson and May (1985).

placenta prior to birth, or through consumption of breast milk following
birth. Mathematically, the result of adding this compartment would be a
time delay between when new individuals are added to the population by
birth and when those individuals become susceptible to infection. Second,
the model by Anderson & May (1985) contains an additional compartment
for those individuals who have been infected, but who are not yet capable
of transmitting the disease organisms to others. This compartment affects
the model in two ways: it prolongs the duration of the epidemic by delaying
the onset of infectiousness; and it reduces the likelihood that random
contacts between an infected individual and other members of the popu-
lation could result in transmission of the infection. Third, the Anderson
& May model does not include disease-related mortality. Some excellent

additional references on modeling human disease transmission are those by Anderson (1982, 1994), Black & Singer (1987), and Doege & Gelfand (1978).

Figure 1.4 shows a model developed by Miller (1979) which describes the epidemic transmission of infection through livestock animals. Miller's model includes vaccination as a means of preventing an initial infection in otherwise susceptible animals. The immunity conferred is not permanent, which allows previously ill or vaccinated animals that remain unslaughtered to return to the pool of susceptibles. Removal of animals in Miller's model occurs through selective slaughter of diseased animals and their contacts, a consciously introduced preventive measure which cannot be used with humans. Miller's model also allows for restocking of the study population, likewise something which cannot be done with human populations. Miller's model includes only one compartment for removed individuals, with movement both into that compartment by slaughter, and back out to the pool of susceptible individuals by restocking. Presumably, a single compartment was used for the sake of simplicity. It is important to understand that, in
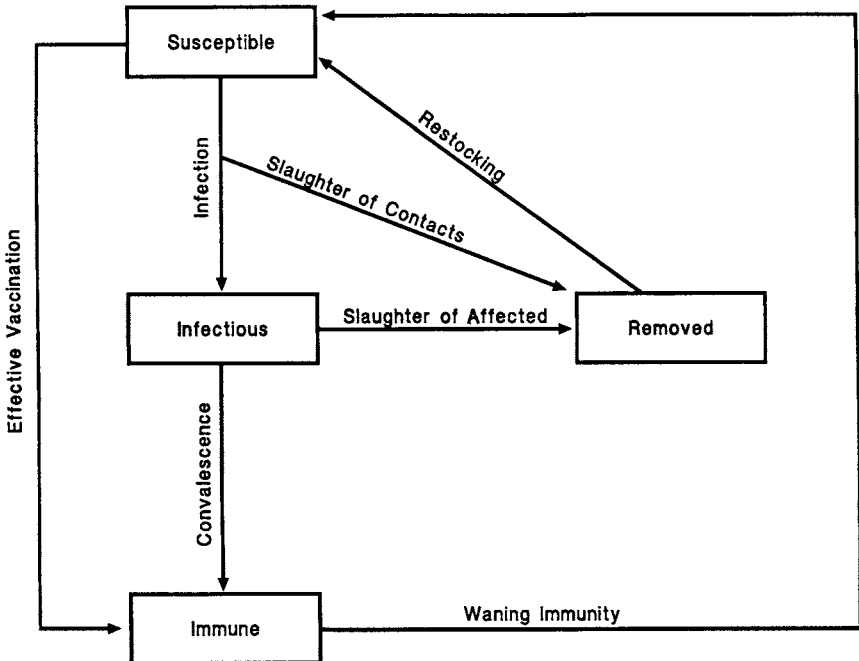

Figure 1.4   Compartment model applicable for long-term epidemic exposure in a livestock population. This model includes removal of both infected and potentially infected individuals, restocking, vaccination as a means of preventing infection, and waning immunity due to passage of time. Redrawn from Miller, 1979.

actuality, the newly restocked individuals cannot come from the same population that was slaughtered, and so we must assume that they come from some outside reserve. A sampling of additional recent examples of models for the transmission of disease through animal populations includes rinderpest in cattle and wild-life, jointly described by James and Rossiter (James & Rossiter, 1989; Rossiter & James, 1989), pseudorabies in swine (Smith & Grenfell, 1990), and rabies in raccoons (Coyne, Smith & Mc-Allister, 1989). Modeling the transmission of disease through plant populations can be almost as simple, but will not be addressed in this book. Cvjetanović (1982) has written an excellent reference on the dynamics of using compartment models to study the transmission of disease through populations. A good general discussion of population modeling appears in the book by Lotka (1956). The remainder of this chapter will only address disease transmission as it relates to humans.

How do infectious agents get transferred between individuals?

The disease transmission models presented in Figures 1.1–1.4 show how diseases are propagated in a population of humans or animals. In Figure 1.1, a side arrow shows the point of disease transmission, where infectious agents are transferred to a susceptible individual. This brings us back to important concepts in disease transmission: there must be a source of the disease agent, there must be a susceptible host and there must be an effective transfer of the agent to the host.

Disease transmission routes can be divided into two broad categories, vertical and horizontal. Vertical transmission occurs between mother and child, either prior to or during the birth process (Mims, 1981; Watson *et al.*, 1993). Horizontal transmission encompasses all other routes, including both environmental and nonenvironmental. Usually, the mother becomes infected with a disease agent that she acquires horizontally, and she then transmits that agent to her fetus vertically.

Diseases can also be classified according to whether their transmission is considered to be 'direct' or 'indirect'. If the infectious agent is incapable of maintaining viability on its own outside the host, or if it can maintain viability in the open environment for only an extremely short period of time, then the disease associated with that infectious agent is assumed to be directly transmitted. Examples of directly transmitted diseases are the bacterial disease gonorrhea, and the viral disease acquired immune deficiency syndrome. Both gonorrhea and acquired immune deficiency syndrome happen to be sexually transmitted, but the concept of directly transmitted disease is not limited to sexual transmission, as it also includes some diseases transmitted through nasal secretions and saliva. Organisms that

are transmitted indirectly are those that can maintain viability in the environment long enough to have sat around, or to have been blown or carried around, before a new host is contacted. Examples of indirectly transmitted diseases are vaccinia, caused by viruses that are released from lesions on the skin and transferred by fomites; and influenza, transmitted by aerosols generated during coughing and sneezing.

All of the infectious agents that are transmitted 'indirectly', plus the majority of 'directly' transmitted infectious agents, are exposed to the environment for some time during their transfer to a new susceptible host. Environmental exposure can occur when the organisms are in aerosols, when they are in contaminated food or water, or when they are on the surface of fomites, the last category consisting of solid environmental objects including toys, clothing and blankets. The major factor that must be considered on the potential for any given infectious agent to be successfully transmitted by an environmental route is the ability of that microorganism to remain viable outside the body of its last host animal, surviving for example in air or water, long enough to encounter a new susceptible host organism.

A disease-causing microbe is less likely to be transmitted by an environmental route that exposes the organism to conditions under which it cannot easily survive. Thus, those infectious agents which are likely to have the greatest success at being transmitted in aerosols or on fomites will logically be the organisms that have evolved resistance to desiccation. Accordingly, it is noted without surprise that both the smallpox and influenza viruses have evolved an ability to survive for long periods of time in air at low relative humidity levels (Harper, 1961). Two other viral diseases that are also suspected of being transmitted via fomites are hepatitis caused by the hepatitis A virus, which in one disease outbreak was possibly acquired from the handling and smoking of cigarettes after infected patients had been cared for in a hospital (Doebbeling, Li & Wenzel, 1993), and gastro-enteritis caused by *Rotavirus* (Keswick *et al.*, 1983), which is common to children at day-care centers. Appropriately, both hepatitis A virus and *Rotavirus* are capable of prolonged survival when exposed to drying on fomites (Abad, Pintó & Bosch, 1994).

Members of the viral genus *Enterovirus* present a good contrast to the smallpox, influenza, hepatitis A and rotaviruses. Generally, the entero-viruses tend to lose viability very rapidly in drying soils and wastewater sludges (Hurst, 1991), and at least one of them, human poliovirus 1, has been shown to possess only minimal ability to survive in air at low relative humidity levels (Harper, 1961) or during drying on fomites (Abad *et al.*, 1994). Their susceptibility to desiccation suggests that, on the whole, enteroviruses are bad candidates for being transmitted by aerosols or on fomites. However, enteroviruses can be detected in wastewater (Melnick, 1947; Melnick *et al.*, 1954*a,b*), where they occur as contaminants during epidemic as well as non-epidemic times (Melnick, 1947), and they are