Journal of Entomology and Zoology Studies

Available online at www.entomoljournal.com

J E Z S Journal of Entomology and Zoology Studies

E-ISSN: 2320-7078
P-ISSN: 2349-6800
JEZS 2018; 6(2): 2731-2738

Received: 21-01-2018
Accepted: 22-02-2018

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Herd immunity: An epidemiological concept to eradicate infectious diseases

S Balakrishnan and V Bhanu Rekha

Abstract
Immunity is the resistance shown by the animals or human beings against infectious pathogens such as virus, bacteria, parasites, rickettsia, protozoa, fungi, moulds, etc. whereas, 'herd immunity' means resistance shown by the proportionate amount of population, preferably 80% of the population. Herd immunity may be innate and acquired, and can be well achieved by mass vaccination. This may be affected by the frequent exposures to the infectious pathogens in the endemic environment, and clinically and subclinically infected population, contiguous and widespread movement nature of the population, irregular pattern of vaccination, basic reproduction number (R_o) of infectious pathogens, import of animals, etc. Hence, prevention and control of infectious diseases is paramount important for sustainable livestock production. Maintaining the herd immunity is the only way to keep disease prevalence at minimum level at which no epidemics, no spread of diseases and insignificant economic loss to the farming community being achieved. This paper reviewed some of the basic concepts on herd immunity and its understanding to implement in the field in the process of eradication of infectious diseases from livestock population.

Keywords: herd immunity - basic concept - innate and acquired – reproduction ratio - mass vaccination - factors affecting

1. Introduction
Infectious diseases among livestock and poultry are distributed worldwide; the type of diseases may vary according to the animal population and ecological pattern of the location [1]. They spread by different modes *viz.*, contact, ingestion, inhalation, skin penetration, coitus and iatrogenic either from one animal to another (horizontal transmission) or from one generation to another generation (vertical transmission) [2]. Climatic change all over the world increases the vector population, thus plays an important role in spread of infectious pathogens [2]. National and international trade of animals and their products, contiguous nature of animal population and unrestricted movement of animals, climatic change and so on lead increased prevalence of diseases, re-emergence of diseases and emergence of exotic new diseases in the animal population throughout the world [3-5].
Prevention, control and eradication of transboundary animal diseases are now taken into consideration by national and international organizations [4]. It should be applied in the population rather than individual animal [2, 4]. A disease in the population is caused not only by a 'necessary cause', the infectious agent (such as virus, bacteria, fungi, parasite, protozoa and rickettsia), also influenced by predisposing, enabling, precipitating and reinforcing factors, the 'component causes' [2]. Apart from this, infectious pathogens follow certain strategies to survive in the host or in the environment, like avoiding the external environment, having wide host range, antigenic shift and/or drift, developing into a resistant form, etc. All these criteria certainly conclude complete eradication of most of the diseases from animal population is a complex problem and paramount task, and great challenge to the Veterinarians all around the world [6-9].
The term 'herd immunity' was coined a century ago [10] and used widely after increasing use of vaccines and vaccination protocols in the process of eradication of diseases. Smith in 1970 [11] and Dietz in 1975 [12] had recognized this concept by explaining a simple 'threshold theorem' in the population mixed at random. Herd immunity has to do with the protection of populations from infection which is brought about by the presence of immune individuals [13]. Protection of livestock against infectious diseases is very important for sustained productivity and well-being of the livestock farmers. The basic principle in establishment of herd immunity is to vaccinate every susceptible individual in the population in a short period of time, and to

create an 'immune barrier/immune belt' which would either prevent entry of infectious agent into the population or reduce the susceptible animals in the population below a critical point of population density [14] at which no disease epidemics occur. Maintaining the herd immunity is the only way to keep away the diseases in animal population at which economic loss is insignificant to the farming community [14]. The concept of herd immunity has got popularity among animal husbandry activities across the world as a consequence of several recent major achievements of vaccination programmes, i.e. the historic success of the global smallpox eradication programme with high infant vaccination coverage have provided "proof of concept" for this relationship [15, 16]; dramatic increases in vaccination coverage stimulated by national programs; the commitment of several countries to eradicate measles; and international dedication to eliminate neonatal tetanus [13] and so on. This paper explains about the basic principles and importance of herd immunity.

2. Understanding the herd immunity

The definition for herd immunity is given by several authors, some use it to describe the proportion immune among individuals in a population; others use it with reference to a particular threshold proportion of immune individuals that should lead to a decline in incidence of infection, and still others use it to refer to a pattern of immunity that should protect a population from invasion of a new infection [17]. A common implication of the term is that the risk of infection among susceptible individuals in a population is reduced by the presence and proximity of immune individuals (this is sometimes referred to as ''indirect protection'' or a ''herd effect'') [17]. Individual immunity is a powerful force affecting host health and pathogen evolution. Importantly, the effects of individual immunity also scale up to affect pathogen transmission dynamics and the success of vaccination campaigns for entire host populations. Population-scale immunity is often termed 'herd immunity' [18].

Proportion of resistant animals in the population is herd immunity and it should be in more than 80% of the population [2, 15, 19]. Herd immunity can be well achieved by mass vaccination. The way of protection from infection of the susceptible individuals in the population, and protection of the population as a whole, this is brought about by the presence of immune individuals [2, 17, 20, 21]. Immune individuals can be created by vaccination at correct age. If this is achieved in almost around 80% of the population in a short span of time would result in strong immune belt against infectious pathogens [20]. It can be possible only by means of mass vaccination. Epizootics of infectious diseases were mainly due to failure mass vaccination [14]. If an infection is to persist, each infected individual must, on average, transmit that infection to at least one other individual. If this does not occur, the infection will disappear progressively from the population [22].

Apart from innate immunity, it may be acquired either naturally or artificially, but if herd immunity is dependent on natural infection, the large proportion of individuals in the population must have exposed with sufficient frequency to an infectious agent and becomes immune [23, 24]. Under any circumstances, the immunity of each individual within the herd must be durable, effective and must prevent transmission rather than just prevent disease. A communicable agent could not be maintained in the animal population when herd immunity is maintained. It could be possible when more than 80% of the population is immune against the pathogen concerned [2, 8, 17].

2.1 Innate herd immunity

Innate herd immunity is been determined by the physiological and genetic phenomenon of the individual [25], but the mechanisms are poorly understood and not yet been adequately explained [26]. Clear understanding of these phenomena and their relationships will help improve the design of effective and efficient immunisation programmes aimed at control, elimination or eradication of vaccine preventable infectious diseases [27]. The immunity which protects the population against infectious diseases other than previous exposure to the pathogens or immunization is said to be innate immunity (e.g. Algerian sheep are resistant to anthrax [28], N'dama cattle are resistant to trypanosomiasis [29, 30], horses are resistant to FMD [31], etc.

2.2 Acquired herd immunity

Development of protective antibodies in a population after natural exposure to the infectious pathogens or immunization is acquired herd immunity [14, 17, 32]. The level of acquired herd immunity after mass vaccination of the population can be determined by the potential efficacy of the vaccine under controlled conditions, the percentage of animals actually vaccinated, percentage of immunologically competent animals among vaccinates percentage of vaccine doses maintained under optimal conditions, percentage of vaccine doses administered properly, etc [14, 17].

3. Probability of disease spread

Herd immunity does not require that every members of the population to be protected. If the proportion of resistant animals is high, there is little risk. The laws of probability for contact are such that only a few sporadic cases usually occur. Thus, the probability of an epidemic depends not only on the proportion of resistant individuals in the herd but also on the frequency of contacts, which reflects the 'social distance' between the individuals likely to spread the disease producing pathogen [2, 8, 9, 33].

A herd-level parameter is valuable because herds are stationary, having only indirect contact with other herds (e.g. through fomites). The concept of effective contact occurring at random within a homogenously mixed population, which forms the basis of simple epidemic models (Fig. 1), is therefore inappropriate [2].

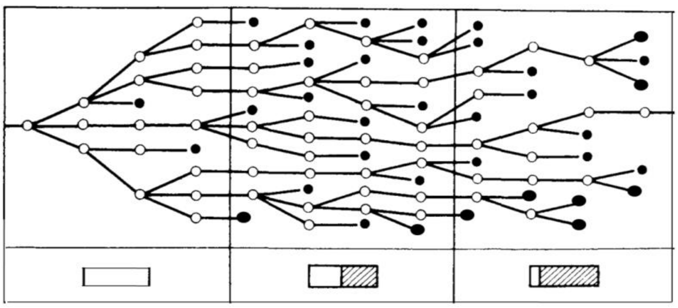

Fig 1: Reed-Frost model [2]: The course of a typical epidemic caused by an infectious agent infecting a totally susceptible population. Each circle represents an infection, and the connecting lines indicate transfer from one case to the next. Black circles represent infected individuals who fail to infect others. Three periods are shown: the first when practically the whole population is susceptible; the second at the height of the epidemic; and the third at the close, when most individuals are immune. The proportions of susceptible (white) and immune (hatched) individuals are indicated in rectangles beneath the main diagram [2]

4. Impact of contact transmission

The occurrence of epidemic outbreaks typically depends on the pathogen and contact patterns between hosts and susceptible individuals [34]. The dynamics of most contact-transmitted infectious processes are such that, if more than 80% of the population made resistant (herd immunity with large-scale vaccination programmes), then large-scale outbreaks fail to occur (Fig. 2) [14, 16, 34]. This fact explains why good protection that is effective levels of herd immunity obtained by mass vaccination eventhough around 80% of the population at risk vaccinated in the population [14].

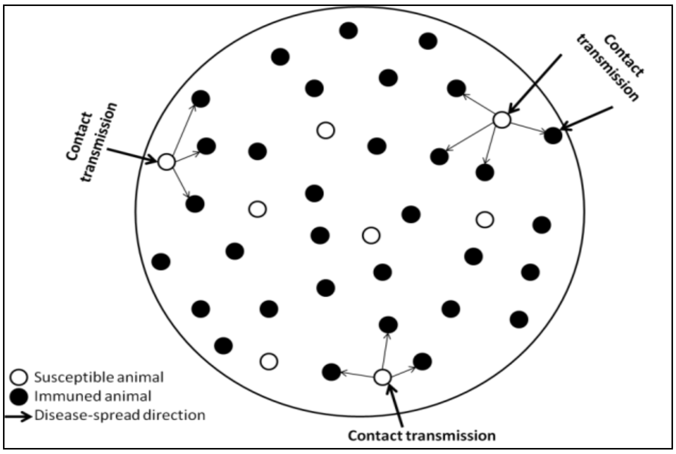

Fig 2: Herd immunity Vs probability of disease transmission: A population consisting of immune animals (black circles) and susceptible animals (white circles) explains that prevention of spread of contact-transmitted diseases (either direct or indirect or aerosol spread) in the population has 80% of immune animals. The susceptible animals in the population not having contact-transmission, explaining that 'immune belt' (i.e. herd immunity) established by the mass vaccination protocols had protected from further spread of the disease. So, spread of disease by contact-transmission has prevented when adequate level of herd immunity was present in the population

The strategy of herd immunity was successful in eradication of rinderpest in India [19, 20, 35]. Why can't we apply the same principle with some modifications for other economically important endemic diseases of livestock (e.g. foot and mouth disease, peste des petits ruminants, bluetongue, sheeppox, goatpox, rabies, anthrax, blackquarter, haemorrhagic septicemia, brucellosis, theileriosis and so on) either to eradicate or reduce rate of communicability and frequency of disease occurrence to the insignificant level.

5. Herd immunity Vs Disease control

Large scale vaccination helps to make the total susceptible population (60 - 80% of the susceptible population) permanently and solidly immune to infection. Population immunity declines when naïve are introduced into the population after their maternally derived antibodies (MDA) have waned. Large scale vaccination programmes have been implemented in various parts of the world for maintaining strong herd immunity [20]. Post-infectious immunity (in surviving animals) as well as post-vaccination immunity proved to be solid in certain diseases like rinderpest, perhaps this may be waned due to recruitment of native animals to the population [20], frequent exposure to the endemic pathogens, unrestricted movement of animals, gathering of animals at common places, etc. Incidences of diseases and sudden clustering more than the expected level of disease frequency often associated with suboptimal vaccine coverage [20]. 'Blitz' vaccination, in which a whole population is vaccinated within a very short span of time, whereas intense mass vaccination is termed as 'immunosterilisation' for rapid elimination infectious pathogens and/or to prevent incursion of infectious diseases [36].

The factors which are very important in achieving herd immunity in the population [14, 37, 38] are

- A good relationship between the veterinarian and the farmer,
- community-based approaches, vaccination at the right time,
- effective and efficient vaccination team,
- self-interested and motivated private practitioners,
- vaccine efficacy,
- proper maintenance of vaccine in the cold chain,
- use of location-specific strains as vaccine candidate,
- time and dose of vaccination,
- deworming the animals before vaccination for gastrointestinal worm burden,
- health status of the animals, age and immune status of the animals,
- endemicity of the disease, and
- adequate information about the mass vaccination to the farming community and animal owners.

6. Duration of herd immunity

The duration of herd immunity is influenced by many factors. Estimation of herd immunity kinetics in the field helped in refining the vaccination schedule under the control programme of foot and mouth disease (FMD). Inverse relationship between the herd immunity and FMD incidences was observed in the States of India following different vaccination practices [39].

6.1 Duration of immunity in each individual animal

Every individual in the population should have adequate level of protective antibodies until the next revaccination schedule. This may be affected by incursion of infectious pathogens in to the immune population, frequency of exposure by the immune individuals with infectious animals or environment, addition of non-immune animals in to the immune population, increase of population size [16, 22, 34, 40], etc.

6.2 Biosecurity

Biosecurity principles such as vaccination, quarantine and segregation, and strategic diagnostic testing determine the duration of herd immunity. Biosecurity remains a great management protocol yet to be efficiently followed by the livestock farmers to keep away all health related issues including infectious diseases [41, 42].

6.3 Vaccination/immunization

The act of administering a vaccine is called vaccination, whereas immunization is the protective response to the vaccine shown by the vaccinated animal, and hence they are competent enough to combat against a specific pathogen. It may reduce the likelihood of development of a disease but may not prevent infection. Vaccinated animals can still get infection when vaccine does not contain the local strains of pathogens or due vaccination or immunization failure [43, 44].

6.4 Eliminating sources of infection

Animal surroundings are occupied by many living (other livestock, birds, insects, rodents, people, etc.) and non-living things (fomites such as manure, soil, surface water, water tanks, feed, and feeding equipment). Herd immunity may be reduced when there is direct or indirect contact with carriers and reservoirs of infectious pathogens. So we must know and understand about how an infectious pathogen survive and spread to eliminate the reservoir and carrier animals. The epidemiological principles like test and slaughter and depopulation/stamping out strategies are used to remove carrier animals from a herd [2, 8, 13, 17].

6.5 Addition of susceptible animals to the herd

It dilutes the proportion of immune population below the level of herd immunity, which make ease incursion of infectious pathogens in to the population. Newly purchased animals from other States or countries first should go for quarantine and then they screened for diseases and vaccinated for the endemic diseases if needed before permitted to introduce in to the population [7, 13, 14, 17, 45].

6.6 Basic reproduction number (R_0)

The average number of secondary infections generated by a single typical infective individual (index case) during its entire infectious period in a totally susceptible non-immune population is known as the basic reproduction number (Fig. 3) [2, 46]. The number of individuals that each infected individual infects at the beginning of an epidemic is formally termed R_0 the basic reproductive ratio of the disease [22]. R_0 is one of the most important ecological/epidemiological metrics for infectious pathogens, and the threshold of R_0 (numeric value 1) determines whether the pathogen is able to persist in the population [47]. In a population, R_o is independent on the number (or proportion) of susceptible or immune individuals. If $R_0 > 1$, an infection will invade a population (there will be more transmission of infection and infection in the population can persist if R_o exceeds one); whereas if $R_0 < 1$ it cannot [2]. The basic reproductive number is not specific to a particular microbe [2]. R_o depends upon population characteristics such as population density and heterogenicity of the population; and pathogen characteristics such as virulence, pathogenicity, infectivity and duration of infectiousness [48, 49].

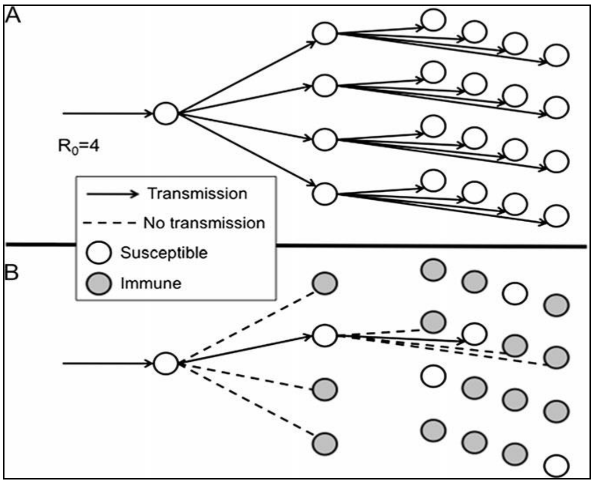

Fig 3: Diagram illustrating transmission of an infection with a basic reproduction number $R_0 = 4$ [17]. A, Transmission over 3 generations after introduction into a totally susceptible population (1 case would lead to 4 cases and then to 16 cases). B, Expected transmissions if $(R_0 - 1)/R_0 = 1 - 1/R_0 = 3/4$ of the population is immune. Under this circumstance, all but 1 of the contacts for each case s immune, and so each case lead to only 1 successful transmission of the infection. This implies constant incidence over time. If a greater proportion is immune, then incidence will decline. On this basis, $(R_0 - 1)/R_0$ is known as the "herd immunity threshold" [17].

The basic reproductive ratio for a macroparasite is defined as the number of daughter worms (or ticks) established in a host population following the introduction of a solitary fertilized female worm (or tick). In both the microparasite and macroparasite cases, the resultant expression for R_0 usually consists of a term for the rates of parasite transmission, divided by an expression for the rate of mortality of the parasite in each stage in the life cycle. Increases in host population size or rates of transmission tend to increase R_0 whereas increases in sources of parasite mortality or decreases in transmission rate tend to reduce the spread of the pathogen through the population [22].

6.7 Increase of population size

Population size may be increased through new purchase, replacement of culling stock, new births, etc. Increase in population size by non-immune animals can lower the level of herd immunity. Hence, the level of herd immunity must be monitored at regular intervals must be important in the population to avoid the spread of diseases [13, 17, 50].

6.8 Departure of immunes through death and emigration

Herd immunity can lower perhaps animals died or sold and moved away from the population. In such circumstances, replacement should be done with immune animals [51].

6.9 Globalization and international trade of animals and products of animal origin

There are many chances for an infectious pathogen to enter in to the susceptible population due to international trade of animals, foods of animal origin, raw materials for animal husbandry activities [4], etc.

6.10 Contiguous nature of animal population

The animal population is in the natures of randomly mixed state throughout the world. Widespread movement of animals due globalization resulted in epidemics and pandemics of certain animals diseases, especially zoonotic diseases, like influenza [52, 53].

6.11 Virulence and infectivity of the agent

Highly virulent pathogen can easily reduce the herd immunity in a short period. Deterioration of herd immunity will be rapid when virulent pathogen circulates among the population [54, 55].

6.12 Antigenic diversity/plurality

Unless the vaccine included with all the endemic strains of an infectious agent, it would not be possible to create complete resistance against all the sub-strains of an infectious pathogen. It needs active surveillance on a particular disease to identify the antigenic plurality in the population following geographical-based molecular investigations. A systematic vaccination programme is ongoing in India to control the three prevailing serotypes (A, O, Asia1) of FMD virus [39].

6.13 Antigenic shift/drift

Emergence of new strain of an infectious agent may result in outbreak of a disease rather than reducing the level of herd immunity. Perhaps for the survival of that pathogen, new strain may emerge [52, 56].

6.14 Ease of agent transmission

It is easy for an infectious agent to invade in to the susceptible population if proportionate resistance in the population is less than 80%. Unauthorized entry of exotic animals, replacement of breeding stocks, increased density of animal population, irregular vaccination protocols, etc. may pave way for incursion of pathogen in to the population [2, 8, 13, 17, 50].

6.15 Duration of shedding of infectious agents by infected animals
Sometimes an infectious pathogen will persist in the animal recovered after infection and shed organisms through several excretions as convalescent carrier or as carrier for lifelong or latent [57] or persistent infection. It pollutes the environment and contaminates the animal surroundings. Susceptible animals may have chance to contact with infectious particles very frequently and the probability of waning of herd immunity would be fast [2, 8, 9, 58]. Infection differs from the disease. Disease will indicate the infection, but infection sometimes subclinical or carrier or reservoir or latent or persistent. Subclinically infected animals may spread the agent to other animals. Resistance to disease may be nonspecific, meaning that the animal is in good enough health to generally fight infection; or specific, because it immune system is prepared with antibodies to defend against a particular disease agent [59].

6.16 Interaction or degree of movement within the population
Frequent interaction and contiguous nature of animal population is circumstance, in which the duration of herd immunity could be reduced to the level at which a pathogen can easily spread among the susceptible individuals in the population [60, 61].

6.17 Minimizing the number of contacts
Sufficient exposure to an infectious agent to develop an infection or disease is called effective contact. We should understand that not every individual exposed to an infectious agent becomes infected or diseased. Duration of contact, frequency of contact, mode of contact, ID_{50} and incubation period may determine the effective contact and subsequent development of an infection/disease [62]. Quarantine, isolation/segregation (often by age or class of animal) and/or dilution of the number of animals over a large geographical area are the epidemiological approaches can reduce the effective contact with disease producing agent. Good management practices and hygienic protocols, immunoprophylaxis and chemeprophylaxis can be followed to reduce the amount of infective dose transferred by contacts between animals [2, 8, 9, 14, 17, 39].

6.18 Global warming and climatic change
New, emerging and re-emerging of new diseases among the animal population were the consequences of climatic change and global warming. When a new disease merged in the livestock population, the complete resistance in the animal population has also broken down. Apart from the increased density of unimmunized animals, the impact of climatic change has significance in the lowering the immune status of animals [63-67].

6.19 Increasing of biological vector population
Vector-borne diseases will always present in the population as long as the vectors are present. Nowadays vector population has also increased because of climatic change. Unless animals are protected from the vectors, it will be a never ending problem and great challenge to the veterinarians to combat against diseases [63, 64, 68, 69].

6.20 Interaction of wild animal reservoirs and domestic animals at ecological interfaces
Infectious agents can easily spread from wild animals to domestic animal population at ecological interface. Biofencing strategy by which domestic animals must have vaccinated against diseases to have adequate level of herd immunity to avoid contraction of infection from wild animals [70, 71]. Several infectious pathogens are endemic in wild animals and follow sylvatic cycle. There will be poor of overt clinical infection. The pathogens are silently present in wild animals as reservoir. When it comes to the domestic cycle, produce overt clinical diseases and outbreaks. Wild animals also act as spillover hosts for several infectious agents [2, 8, 9, 72-75].

7. Conclusions
The presence of infectious pathogens in animals, humans and environment is never lasting. At the same time, the loss (in terms of productivity, cost of veterinary health care interventions, morbidity and mortality) due to these pathogens in animal population must be either completely stopped or reduced some level at which there is no significant losses to the farming community. How best this can be achieved is the question of the hour throughout the world. All means of directed actions against diseases (example: prevention, control, eradication, etc.) aim at protecting the maximum number of susceptible individuals at risk, typically with a combination of mass vaccination of high risk populations and good management practices. Importantly, the infectious pathogen's communicability chain has to be broken down to prevent the spread of pathogens from one animal to another under field/herd circumstances. These strategies require understanding of herd immunity. Maintenance of herd immunity is a stepping stone to achieve 'disease free zone', which could lead to either total eradication or regional eradication of any infectious pathogen from the susceptible population. Indeed, as the proverbs say that, "prevention is better than cure" and "health is wealth", mass vaccination of animal population is easier than any other directed actions against diseases in developing countries like India.

8. Acknowledgement
The authors thank to the Dean, Veterinary College and Research Institute, Orathanadu for providing facilities to carry out the present work.

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