Concepts of herd immunity and protection

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Plan of talk

- Introduce herd immunity, herd effects and herd protection
- Simple example of how herd immunity operates
- Concepts of basic reproductive number ($R_0$) and effective reproductive number
- Herd immunity threshold in context of infection elimination for different diseases
- Beneficial and harmful effects of increasing herd immunity
- Measurement of direct and indirect effects of vaccines in trials
What is herd protection?

• Herd protection is generally discussed in the context of vaccines – but the concept has wider applicability.

• Simplistically, it is used when intervention measures applied to individuals have a greater effect at a population (herd) level than simply the sum of the effects on the individuals to which the intervention is applied.

• The “whole is greater than the sum of the parts”

• More specifically the beneficial effects may extend to those to whom the intervention is not applied and these (indirect) effects will increase in magnitude according to coverage of the population with the intervention.

• Furthermore, the individual benefit of an intervention to a recipient may increase according to the proportion of other individuals in the population who receive the intervention.

• Examples: many vaccines; deworming programmes; insecticide impregnated bed-nets
Why is herd protection important?

• Many interventions, including vaccines specifically, are licensed/evaluated on the basis of randomised controlled trials (RCTs) – which are designed to assess the level of individual protection/benefit that the intervention confers to the recipient. Difficult to measure indirect effects.

• If there are herd protective effects when the intervention is in public health use then RCTs may underestimate the benefit of the intervention and the benefit/cost ratio will be underestimated based on RCT results.

• Furthermore, the extent of disease/infection control that can be achieved by application of the intervention may be underestimated and the coverage required for a given level of disease control (or even elimination) will be overestimated. For “expensive” interventions this may affect decisions about public health deployment.

• Should (pre/post-licensure) trials be designed to measure the population-level impact of an intervention and/or through modelling?
The number of individuals in a population (herd) who are (relatively) immune to infection with an infectious agent may depend on the proportion who have previously been infected with the agent and the proportion who have been vaccinated with an efficacious vaccine.

A measure of the level of population-immunity or **herd-immunity** is the proportion who are thus immune from further infection (John & Samuel 2000).

For many infections, the level of herd immunity may have an effect on the transmission of the infection within the population and, in particular, *may affect the risk of an uninfected becoming infected.*

For such infections, increasing the level of herd immunity will decrease the risk of an uninfected person becoming infected.
Vaccines: herd immunity, herd effects and herd protection

• For some infections this **herd effect** or **herd protection** may be very important for disease control through vaccination.

• If the herd effect reduces the risk of infection among the uninfected sufficiently then the infection may no longer be sustainable within the population and the infection may be eliminated.

• This concept is important in disease elimination or eradication programmes. It means, for example, that elimination can be achieved without necessarily vaccinating the entire population.
• Infections for which herd immunity may be important in reducing the risk of infection in non-immunes in the population are those:
  – which are transmitted directly from person to person (e.g. measles, rubella, varicella)
  – for which humans are the reservoir, or an important reservoir of infection (e.g. polio, malaria)

• There may be no herd protection if human are not an important reservoir of infection (e.g. tetanus, rabies)
No herd immunity

First generation

Uninfected susceptible
No herd immunity

First generation

Uninfected susceptible
Infected infectious
No herd immunity

First generation

Uninfected susceptible
Infected infectious

basic reproductive number
$R_0 = 2$
Basic Reproductive Number

The basic reproductive number (R<sub>0</sub>) is the average number an infectious person will infect with an agent in a completely susceptible population.

R<sub>0</sub> will vary from agent to agent depending on the infectiousness of the agent – e.g.

- how long it survives in the environment
- the dose necessary for infection
- the duration of infectiousness in the host
- Whether or not infectiousness precedes infection symptoms

R<sub>0</sub> may also vary from population to population depending on factors such as population density, which may affect the number of effective contacts a person has while they are infectious.
No herd immunity

First generation

Uninfected susceptible

Infected infectious

basic reproductive number

$R_0 = 2$
No herd immunity

First generation

Second generation

basic reproductive number

$R_0 = 2$

Uninfected
susceptible

Infected
infectious
No herd immunity

First generation

Second generation

Uninfected susceptible
Infected infectious

Attack rate among susceptibles in 2^{nd} generation = 4/16 (25%)

basic reproductive number

R_0 = 2
No herd immunity

First generation

Second generation

Uninfected susceptible

Infected infectious
Herd immunity with vaccination

- First generation
  - First infected
  - First protected
- Second generation
  - Second infected
  - Second protected

- Uninfected
- Infected
- Vaccinated
- Susceptible
- Protected
Herd immunity with vaccination

- Uninfected susceptible
- Infected infectious
- Vaccinated protected

Indirectly protected

Second generation

Effective reproductive number

\( R = 1 \)
**Herd immunity with vaccination**

- Uninfected
- Susceptible
- Infected
- Infectious
- Vaccinated
- Protected

Attack rate among susceptibles in 2nd generation = $\frac{1}{8} (12.5\%)$

Effective reproductive number $R = 1$
No herd immunity

First generation

Second generation

Uninfected susceptible

Infected infectious

Attack rate among susceptibles in 2nd generation = 4/16 (25%)

basic reproductive number

$R_0 = 2$
Disease elimination

• If the herd effect reduces the risk of infection among the uninfected sufficiently then the infection may no longer be sustainable within the population and the infection may be eliminated.

• The “effective reproduction number” (R) has to be reduced below 1.

• If a proportion P of the population are immune then $R = (1 - P) R_0$

• So, to get R down to about 1, P must be up to $1 - 1 / R_0$

• Thus if $R_0 = 5$ then vaccine coverage will have to be in excess of 80%

• (In reality, life is more complicated because population mixing is not homogeneous, etc.)
(Approximate) Herd Immunity Thresholds for Infection Elimination

<table>
<thead>
<tr>
<th>Infection</th>
<th>$R_o$</th>
<th>Herd immunity threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diphtheria</td>
<td>6-7</td>
<td>~85%</td>
</tr>
<tr>
<td>Measles</td>
<td>12-18</td>
<td>83-94%</td>
</tr>
<tr>
<td>Mumps</td>
<td>4-7</td>
<td>75-86%</td>
</tr>
<tr>
<td>Pertussis</td>
<td>12-17</td>
<td>92-94%</td>
</tr>
<tr>
<td>Polio</td>
<td>5-7</td>
<td>80-86%</td>
</tr>
<tr>
<td>Rubella</td>
<td>6-7</td>
<td>83-85%</td>
</tr>
<tr>
<td>Smallpox</td>
<td>5-7</td>
<td>80-85%</td>
</tr>
<tr>
<td>Pandemic flu (H1N1)</td>
<td>1.6?</td>
<td>~40%</td>
</tr>
</tbody>
</table>

Partly taken from Fine (1993)
Herd immunity, herd effects and herd protection

Increasing the level of herd immunity may have beneficial and deleterious effects

**Beneficial effects**

- Potential for infection elimination
- Reduced risk of infection for those refusing vaccination (“free riders”)
- Reduced risk of infection for those for whom vaccination is contraindicated (e.g. immunosuppressed)

**Deleterious effects**

- Raise the average age of infection among those who are infected
  - Particular problem for those infections where the severity of infection increases with age (e.g. polio, rubella, varicella, measles, hepatitis A)
Measurement of direct and indirect effects of vaccination

Popn.1

Popn.2

- vaccinated
- unvaccinated
Measurement of direct and indirect effects of vaccination

Direct effect of vaccination – incidence in vaccinated compared to incidence in unvaccinated
Measurement of direct and indirect effects of vaccination

Indirect effect of vaccination – incidence in unvaccinated in Popn.1 compared to incidence in unvaccinated in Popn.2
Measurement of direct and indirect effects of vaccination

Overall effect of vaccination – incidence in Popn.1 compared to incidence in Popn.2
Measurement of direct and indirect effects of vaccination

Total effect of vaccination:
– incidence in vaccinated in Popn. 1 compared to incidence in unvaccinated in Popn. 2

Popn.1

Popn.2

- vaccinated
- unvaccinated
Measurement of direct and indirect effects of vaccination

Direct effect of vaccination – incidence in vaccinated compared to incidence in unvaccinated

Indirect effect of vaccination – incidence in unvaccinated in Popn.1 compared to incidence in unvaccinated in Popn.2

Overall effect of vaccination – incidence in popn.1 compared to incidence in popn.2

Total effect of vaccination: – incidence in vaccinated in Popn. 1 compared to incidence in unvaccinated in Popn. 2
Thank you!