Considerations of infectious disease modelling in public health policy

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Mathematical models of infectious diseases

• Public health agencies increasingly depend on epidemiological transmission models
  – Estimate likely impact of an epidemic
  – Plan for effective design of control measures

• Recent examples
  – “Swine flu” H1N1\(v\) 2009
  – HIV
  – Vaccines: HPV, pneumococcal
Basic principles of infectious disease

One person infects people, then they infect people...
One person infects people, then they infect people…
One person infects people, then they infect people…

Basic principles of infectious disease
The most important quantity governing an epidemic is how many other people one person infects.

The *Basic Reproduction Number* $R_0$. 

Basic reproductive number, $R_0$
The most important quantity governing an epidemic is how many other people one person infects.

The Basic Reproduction Number $R_0$.

Needs to be $>1$ for an epidemic
Rate of new infections

establishment

exponential growth

Epidemic curve

Time

Random effects

Ferguson et al Nature 2003
Epidemic curve

Rate of new infections vs. Time

- establishment
- exponential growth
- exhaustion of susceptibles
- Equilibrium, or recurrent epidemics
- endemicity

Random effects

Ferguson et al Nature 2003
Each infection is dependent on previous events.

$R_0 = 3$
Protecting one individual has indirect protective effects on others.

Because of ‘indirect protection’

Protecting one individual has indirect protective effects on others.
Vaccination

• Critical vaccination fraction
  – Vaccinate proportion, $p$, of the population
  – $1-p$ are unprotected
  – ‘Effective R0’ is
    \[ R_{0v} = R_0(1-p) \]
Example:

- $$R_0 = 3$$
- Proportion of population vaccinated: $$p = 1/3$$
- Proportion unvaccinated: $$(1-p) = 2/3$$
Example:

\[ R_0 = 3 \]

Proportion unvaccinated

\[ (1-p) = \frac{2}{3} \]
Vaccination

Example:

\[ R_0 = 3 \]

Proportion unvaccinated

\[ (1-p) = \frac{2}{3} \]

Mean no. infections

\[ = \frac{2 + 1 + 3}{3} = 2 \]

Mean no. infections

\[ = (1-p) R_0 = 2 \]
Vaccination

• Critical vaccination fraction
  – Vaccinate proportion, $p$, of the population
  – $1-p$ are unprotected
  – ‘Effective R0’ is
    \[ R_{0v} = R_0(1-p) \]
  – Want this to be less than 1
    \[ R_{0v} < 1 \quad \text{and} \quad R_0(1-p) < 1 \]
Vaccination

- Critical vaccination fraction
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    $$R_{0v} < 1 \quad R_0 (1-p) < 1$$

$$p > p_c = 1 - \frac{1}{R_0}$$
Critical vaccination threshold

Flu, SARS
Childhood infections

Depends on CONTACT patterns
Heterosexual mixing

• Critical vaccination coverage depends on contact rates of men and women

\[ v_c = 1 - \frac{1}{R_{0,f} R_{0,m}} \]
Heterosexual mixing
Heterosexual mixing

Vaccinating half of one sex.
Direct effect, half of cases in that sex prevented.
Heterosexual mixing

Vaccinating half of one sex.

Indirect effect in BOTH sexes
Heterosexual mixing

Vaccinating half of one sex.

Indirect effect in BOTH sexes

Vaccinating other sex, effect is ‘diluted’
Heterosexual mixing

• Critical vaccination coverage depends on contact rates of men and women
  \[ v_c = 1 - \frac{1}{R_{0,f} R_{0,m}} \]

• If men and women are identical
  – at “sub-critical” levels, want to concentrate vaccination on one sex
  – Avoid ‘dilution’ of vaccine on contacts between men and women who are both vaccinated

• BUT, the real picture is more complicated

Sexual Contacts

- Contact surveys
  - Sensitive
  - Some “desirability bias” issues
  - Defining types of sexual contact
- High degrees of heterogeneity

Gregson et al Lancet 2002
Critical vaccine coverage for heterogeneous mixing

- Highly active groups can over-contribute to transmission
- Requires higher vaccine coverage to capture them
- Targetted vaccination campaigns in these groups are possible for some infections

Coverage and behaviour

• Is probability of being vaccinated correlated with that of your contacts?
  – Leads to larger outbreaks amongst these networks than if they were randomly distributed, e.g. Measles in the Swansea, UK, 2013

• Is the probability of being vaccinated is correlated with having low sexual risk behaviour?
  – Low coverage in the most active groups will reduce the impact of a campaign
Estimating future incidence and validating mathematical models

• Bringing together different data sources
  – Historic sexual behaviour data
  – Retrospective surveys of behaviour
  – Age-specific serology

• Understanding sources of uncertainty
  – Which are most influential in determining intervention outcome in the models?
    • Types of risk behaviour – oral sex
    • What is the pathway to cancer – multiple infections, duration of infection
    • Timescales – duration of protection, natural immunity, time to develop cancer

• Many publications, mostly related to cervical cancer. Possible starting points:
  – Garnett et al Vaccine 2006