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Atmospheric dispersion modelling of bioaerosols that are pathogenic to humans and livestock – A review to inform risk assessment studies

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ABSTRACT

In this review we discuss studies that applied atmospheric dispersion models (ADM) to bioaerosols that are pathogenic to humans and livestock in the context of risk assessment studies. Traditionally, ADMs have been developed to describe the atmospheric transport of chemical pollutants, radioactive matter, dust, and particulate matter. However, they have also enabled researchers to simulate bioaerosol dispersion.

To inform risk assessment, the aims of this review were fourfold, namely (1) to describe the most important physical processes related to ADMs and pathogen transport, (2) to discuss studies that focused on the application of ADMs to pathogenic bioaerosols, (3) to discuss emission and inactivation rate parameterisations, and (4) to discuss methods for conversion of concentrations to infection probabilities (concerning quantitative microbial risk assessment).

The studies included human, livestock, and industrial sources. Important factors for dispersion included wind speed, atmospheric stability, topographic effects, and deposition. Inactivation was mainly governed by humidity, temperature, and ultraviolet radiation.

A majority of the reviewed studies, however, lacked quantitative analyses and application of full quantitative microbial risk assessments (QMRA). Qualitative conclusions based on geographical dispersion maps and threshold doses were encountered frequently. Thus, to improve risk assessment for future outbreaks and releases, we recommended determining well-quantified emission and inactivation rates and applying dosimetry and dose–response models to estimate infection probabilities in the population at risk.

1. Introduction

1.1. Perspective on bioaerosols

Aerobiology is the research area focusing on the generation and transport of *bioaerosols*. Bioaerosols are small, airborne particles consisting of biological material (from bacteria, viruses, spores, fungi, algae, protozoa, and pollen) either attached to particulate matter or not (Bovallius and Roffey, 1987; Després et al., 2012; Dungan, 2010; Gilbert and Duchaine, 2009; Griffin, 2007; Stärk, 1999; Wéry, 2014). Large amounts of bioaerosols are produced each year by sources including the natural environment and livestock farms (Cambra-López et al., 2010; Viana et al., 2008).

Pathogenic or *infectious* bioaerosols possibly cause respiratory infections after penetration into the respiratory system of humans or animals (Stärk, 1999; Stuart and Wilkening, 2005; Wéry, 2014). The pathogenicity to cause disease is dependent on the pathogen's infectivity, and its ability to be transported and to survive (Anderson and Bokor, 2012; Kersh et al., 2013; La Scola and Raoult, 2001; Rousset et al., 2009). After being emitted or aerosolised from its source, dispersion to the surrounding environment (nearby residents, livestock, etc.) may occur. However, large-scale measurements are not generally available, time-consuming and expensive, thus complicating pathogen quantification. Also, pathogens may be inactivated in the air as well (e.g., by temperature or humidity), (Després et al., 2012; Griffiths and DeCosemo, 1994; Verreault et al., 2008).

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1.2. Atmospheric dispersion models

Atmospheric dispersion models (ADMs) may be helpful to describe the dispersion of pathogenic bioaerosols. ADMs are mechanistic models describing the transport of gases and particles – including chemical pollutants, radioactive matter, particulate matter, and dust – in the atmosphere in space and time (Holmes and Morawska, 2006; Markiewicz, 2012; Potempski et al., 2008). ADMs are widely used in the risk assessment of hazardous effects of air pollution on humans and the environment (e.g., Schaap et al., 2013). Sources are classified as either continuous (e.g., air and odour quality monitoring of emissions from industry or animal housing) or instantaneous (e.g., release of hazardous material from large fires in industrial buildings).

The advantage of mechanistic models is that they incorporate physical processes describing dispersion and that they are able to predict the dispersion process based on measurements (Kuparinen, 2006). Furthermore, most measurements are point samples in space and/or time, but ADMs can predict concentrations at high spatial and temporal resolutions. During an outbreak they may efficiently provide information, either to inform sampling or for the benefit of other response functions, such as vaccination or distribution of antibiotics (Stuart and Wilkening, 2005).

Historically, ADMs were often based on the Gaussian dispersion equation (see Section 2.4; Markiewicz, 2012, Millner, 2009) to calculate concentrations at local scales (<30 km) in a three-dimensional frame. Nowadays, most ADMs include important atmospheric processes related to fluid dynamics (e.g., turbulence) as well (Nathan et al., 2005; Upper and Hirano, 1991). Some also simulate trajectories of backward and forward spatial motions, or dispersion of so-called pollutant puffs. Furthermore, increased computer power has stimulated the development of models based on computational fluid dynamics (CFD) that include landscape features such as buildings and trees (Nathan et al., 2005; Westbrook and Isard, 1999).

Although ADMs were initially developed to simulate chemical pollutant dispersion, they have enabled researchers to simulate dispersion of bioaerosols at different spatial and temporal scales and resolutions (Després et al., 2012). Moreover, by using quantitative estimates of emission rates (i.e. the amount of pathogen emitted per unit of time, see Section 2.2), airborne concentrations (representing exposure) can be converted to doses using dosimetry models (see Section 3) to subsequently perform a quantitative microbial risk assessment (QMRA) (Paez-Rubio et al., 2007; Upper and Hirano, 1991).

ADMs are useful to address concerns about public health risks related to exposure from, for instance, livestock sources and sources related to biosafety agents (e.g., *Bacillus anthracis* and *Coxiella burnetii*) (Anderson and Bokor, 2012; Smit et al., 2012). In addition, ADMs are particularly useful in case of future outbreaks or releases. Knowledge of pathogen emission, host-susceptibility, and complex atmospheric processes may help professionals to assess and to reduce airborne infection risks (Westbrook and Isard, 1999).

1.3. Aim and outline

The objectives of this review were to present an overview of:

- the most important physical processes related to atmospheric dispersion modelling and pathogen transport (Section 2),
- studies that focused on the application of ADMs to simulate airborne transmission of pathogenic bioaerosols (Section 4),
- parameterisations regarding emission and inactivation in these ADM studies (Section 5), and
- methods for conversion of concentrations to infection probabilities applied (concerning quantitative microbial risk assessment) in the ADM studies (Sections 3 and 6),

and to place these in the context of risk assessment modelling. We focused on pathogenic bioaerosols transmitted in the outdoor environment causing airborne infections in humans and livestock. Our focus was not on direct human–human or animal–animal transmission. We used the word *pathogen* in the context of pathogenic bioaerosols. Tables 1 and 2 list respectively all abbreviations and parameters used in this review. Table 3 lists all atmospheric dispersion models discussed in this review. Appendix A lists all studies reviewed in Section 4.

Table 1
List of abbreviations.

Pathogens	
AIV	Avian influenza virus
FMDV	Foot-and-mouth-disease virus
PRV	Pseudorabies virus
SARS	Severe Acute Respiratory Syndrome
Atmospheric dispersion models	
ADMS	Atmospheric Dispersion Modelling System
AERMOD	AMS/EPA Regulatory Model
ALOHA	Areal Locations of Hazardous Atmospheres
CALPUFF	Californian Puff model
DERMA	Danish Emergency Response Model of the Atmosphere
DREAM	Dust Regional Atmospheric Model
GIADA	Guida Interattiva ad Applicazione per la Dispersione Atmosferica
HPAC	Hazard Prediction and Assessment Capability
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory model
INPUFF	Integrated PUFF model
LODI	Lagrangian Operational Dispersion Integrator
MLCD	Modèle Lagrangien Courte Distance
NAME	Numerical Atmospheric-dispersion Modelling Environment
OMEGA	Operational Multiscale Environment Model with Grid Adaptivity
OPS-ST	Operational Priority Substances Short Term model
RIMPUFF	Risø Mesoscale PUFF model
Meteorological models	
ECMWF	European Centre for Medium-Range Weather Forecasts
HiRLAM	High Resolution Limited Area Model
LAPS	Limited Area Prediction System (ABM)
MM5	Fifth-generation Penn State/NCAR Mesoscale Model
NCEP/NCAR	Numerical Weather Prediction model of NCEP and NCAR
Institutes	
ABM	Australian Bureau of Meteorology (Australia)
AMS	American Meteorological Society (USA)
DWD	German Weather Service (Deutsche Wetter Dienst) (Germany)
EPA	Environmental Protection Agency (USA)
KMAA	Korean Meteorological Administration Agency (South-Korea)
KNMI	Royal Netherlands Meteorological Institute (The Netherlands)
NCAR	National Center for Atmospheric Research (USA)
NCEP	National Centers for Environmental Prediction (USA)
NMI	Norwegian Meteorological Institute (Norway)
NOAA	National Oceanic and Atmospheric Administration (USA)
Other	
CFD	Computational Fluid Dynamics
CFU	Colony forming units
DR	Dose–response
GDAS	Global Data Assimilation System
ID_{50}	Median infectious dose
IU	Infectious unit
LD_{50}	Median lethal dose
NWP	Numerical Weather Prediction (model)
PSD	Particle size distribution
QMRA	Quantitative microbial risk assessment
SIR	Susceptible-Infected-Recovered
$TCID_{50}$	Median tissue culture infectious dose
WWTP	Wastewater treatment plant

2. Atmospheric dispersion models

2.1. Physical processes

Five major processes are related to the number of infections caused by airborne pathogens:

(1) The amount of pathogen released per unit of time (emission rate), being a function of pathogen availability and the aerosolisation rate (Shao, 2008; Viana et al., 2008; see Section 2.2).

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