

**The IMA Volumes
in Mathematics
and its Applications**

Volume 126

Series Editor
Willard Miller, Jr.

Institute for Mathematics and its Applications IMA

The **Institute for Mathematics and its Applications** was established by a grant from the National Science Foundation to the University of Minnesota in 1982. The IMA seeks to encourage the development and study of fresh mathematical concepts and questions of concern to the other sciences by bringing together mathematicians and scientists from diverse fields in an atmosphere that will stimulate discussion and collaboration.

The IMA Volumes are intended to involve the broader scientific community in this process.

Willard Miller, Jr., Professor and Director

* * * * *

IMA ANNUAL PROGRAMS

1982–1983	Statistical and Continuum Approaches to Phase Transition
1983–1984	Mathematical Models for the Economics of Decentralized Resource Allocation
1984–1985	Continuum Physics and Partial Differential Equations
1985–1986	Stochastic Differential Equations and Their Applications
1986–1987	Scientific Computation
1987–1988	Applied Combinatorics
1988–1989	Nonlinear Waves
1989–1990	Dynamical Systems and Their Applications
1990–1991	Phase Transitions and Free Boundaries
1991–1992	Applied Linear Algebra
1992–1993	Control Theory and its Applications
1993–1994	Emerging Applications of Probability
1994–1995	Waves and Scattering
1995–1996	Mathematical Methods in Material Science
1996–1997	Mathematics of High Performance Computing
1997–1998	Emerging Applications of Dynamical Systems
1998–1999	Mathematics in Biology
1999–2000	Reactive Flows and Transport Phenomena
2000–2001	Mathematics in Multimedia
2001–2002	Mathematics in the Geosciences
2002–2003	Optimization
2003–2004	Probability and Statistics in Complex Systems: Genomics, Networks, and Financial Engineering

Continued at the back

Carlos Castillo-Chavez
with
Sally Blower, Pauline van den Driessche,
Denise Kirschner, and Abdul-Aziz Yakubu
Editors

Mathematical Approaches
for Emerging and Reemerging
Infectious Diseases:
Models, Methods, and Theory

With 69 Illustrations



Springer

Carlos Castillo-Chavez, Director
Mathematical and Theoretical Biology Institute
and member, Departments of Biometrics, Statistics and Theoretical and Applied Mechanics
Cornell University
Ithaca, NY 14853-7801
USA
cc32@cornell.edu
http://www.biom.cornell.edu/Homepages/Carlos_Castillo-Chavez/

Sally Blower
Department of Biomathematics
UCLA School of Medicine
Los Angeles, CA 90095-1766
USA
SBlower@biomath.medsch.
ucla.edu

Pauline van den Driessche
Department of Math and Stats
University of Victoria
Victoria, British Columbia
V8W 3P4
Canada
pvdd@math.uvic.ca

Denise Kirschner
Dept. of Microbiology and
Immunology
University of Michigan Medical
School
Ann Arbor, MI 48109-0620
USA
kirschne@umich.edu

Abdul-Aziz Yakubu
Department of Mathematics
Howard University
Washington, DC 20059
USA
ayakubu@fac.howard.edu
or Biometrics Department
Cornell University
Email: ay32@cornell.edu

Series Editor:
Willard Miller, Jr.
Institute for Mathematics and
its Applications
University of Minnesota
Minneapolis, MN 55455
USA

Mathematics Subject Classification (2000): 92-01, 92-02, 92-06, 92B05, 92D25, 92D30, 92D40, 37N25, 34C60, 34D23, 37C75, 34K60, 39A11, 39-06, 45-06, 60J80

Library of Congress Cataloging-in-Publication Data

Mathematical approaches for emerging and reemerging infectious diseases.

Models, methods, and theory / editors, Carlos Castillo-Chavez . . . [et al.].

p. cm. — (The IMA volumes in mathematics and its applications ; 126)

Includes bibliographical references and index.

ISBN 978-1-4612-6550-4 ISBN 978-1-4613-0065-6 (eBook)

DOI 10.1007/978-1-4613-0065-6

1. Communicable diseases—Epidemiology—Mathematical models—Congresses. I. IMA volumes in mathematics and its applications ; v. 126.

RA643 .M352 2001

614.5'01'51—dc21

2001049541

Printed on acid-free paper.

© 2002 Springer Science+Business Media New York
Originally published by Springer-Verlag New York, Inc. in 2002
Softcover reprint of the hardcover 1st edition 2002

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher Springer Science+Business Media, LLC, except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use of general descriptive names, trade names, trademarks, etc., in this publication, even if the former are not especially identified, is not to be taken as a sign that such names, as understood by the Trade Marks and Merchandise Marks Act, may accordingly be used freely by anyone.

Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by Springer Science+Business Media, LLC provided that the appropriate fee is paid directly to Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, USA (Telephone: (508) 750-8400), stating the ISBN number, the title of the book, and the first and last page numbers of each article copied. The copyright owner's consent does not include copying for general distribution, promotion, new works, or resale. In these cases, specific written permission must first be obtained from the publisher.

Production managed by A. Orrantia; manufacturing supervised by Jeffrey Taub.
Camera-ready copy prepared by the IMA.

9 8 7 6 5 4 3 2 1

ISBN 978-1-4612-6550-4

SPIN 10850724

FOREWORD

This IMA Volume in Mathematics and its Applications

MATHEMATICAL APPROACHES FOR EMERGING AND REEMERGING INFECTIOUS DISEASES: MODELS, METHODS AND THEORY

is based on the proceedings of a successful one week workshop. The proceedings of the two-day tutorial which preceded the workshop "Introduction to Epidemiology and Immunology" appears as IMA Volume 125: Mathematical Approaches for Emerging and Reemerging Infectious Diseases: An Introduction. The tutorial and the workshop are integral parts of the September 1998 to June 1999 IMA program on "MATHEMATICS IN BIOLOGY."

I would like to thank Carlos Castillo-Chavez (Director of the Mathematical and Theoretical Biology Institute and a member of the Departments of Biometrics, Statistics and Theoretical and Applied Mechanics, Cornell University), Sally M. Blower (Biomathematics, UCLA School of Medicine), Pauline van den Driessche (Mathematics and Statistics, University of Victoria), and Denise Kirschner (Microbiology and Immunology, University of Michigan Medical School) for their superb roles as organizers of the meetings and editors of the proceedings. Carlos Castillo-Chavez, especially, made a major contribution by spearheading the editing process. I am also grateful to Kenneth L. Cooke (Mathematics, Pomona College), for being one of the workshop organizers and to Abdul-Aziz Yakubu (Mathematics, Howard University) for serving as co-editor of the proceedings. I thank Simon A. Levin (Ecology and Evolutionary Biology, Princeton University) for providing an introduction.

Finally, I take this opportunity to thank the National Science Foundation (NSF), whose financial support of the IMA made the Mathematics in Biology program possible, and the National Institute of General Medical Sciences of the National Institutes of Health (NIH), for providing partial support for the workshop.

Willard Miller, Jr., Professor and Director
Institute for Mathematics and its Applications
University of Minnesota
400 Lind Hall, 207 Church St. SE
Minneapolis, MN 55455-0436
612-624-6066, FAX 612-626-7370
miller@ima.umn.edu
World Wide Web: <http://www.ima.umn.edu>

PREFACE

MATHEMATICAL APPROACHES FOR EMERGING AND REEMERGING INFECTIOUS DISEASES: MODELS, METHODS AND THEORY

The research collected in the volume 125, *Mathematical Approaches for Emerging and Reemerging Infectious Diseases: An Introduction* and IMA Volume 126, *Mathematical Approaches for Emerging and Reemerging Infectious Diseases: Models, Methods and Theory*, grew out of the discussions and presentations instigated by the Workshop on Emerging and Reemerging Diseases sponsored by the Institute for Mathematics and its Applications (IMA) at the University of Minnesota in May 17–21, 1999. This workshop included a two day tutorial session directed to ecologists, epidemiologists, immunologists, mathematicians and scientists interested in being exposed to some of the modeling and mathematical approaches used in the study of disease dynamics. Tutorial papers presented at this workshop or requested, as a result of the nature of the contributions of workshop participants, have been included (mostly) in the introductory volume. On the other hand, this volume includes papers on applications that may require additional mathematical sophistication. The reader will find applications motivated by the study of diseases like Influenza, HIV, Measles and Tuberculosis. There are also two contributions to the study of macroparasitic diseases like schistosomiasis.

These volumes are dedicated to Fred Brauer and Kenneth Cooke on their retirement from their academic positions at the University of Wisconsin-Madison and Pomona College, respectively. The leading articles in each volume take a personal look at their contributions to mathematics, mathematical biology and epidemiology over the past five decades. It is but a small gesture of our appreciation as we continue to learn from our personal and professional association to these leading researchers and extraordinary teachers and mentors.

The last two contributions in IMA Volume 125 are co-authored by Angel Capurro who died suddenly in a car accident on December 10, 2000. Angel was a leading researcher at the Departamento de Investigaciones of the Universidad de Belgrano in Buenos Aires Argentina for the past six years. Angel, in a very short time, established one of the most active research groups on the study of tuberculosis. He was not only a leading researcher in the field of tuberculosis but also active in ecology with an appointment at the Universidad Nacional in Lujan, Argentina. Angel was a wonderful individual with friends all over the world. He was a close friend of many of us, and we will miss him.

We want to thank Simon A. Levin for writing the introduction and for encouraging and supporting the completion of these two volumes. We spent various amounts of time at the IMA in 1998 and 1999 and earlier during the preparation of many of the activities associated with the organization of the 1998-99 IMA Special Year in Mathematical Biology. We also want to express our gratitude to those individuals who were responsible not only for the support of the activities associated with the preparation of these volumes but also to those members of IMA's staff who made our visit to this institute a wonderfully productive experience. The leadership and support of Willard Miller and Fred Dulles are highly appreciated. We also want to acknowledge the help and friendliness of Kathy Boyer, Inés Foss, Michelle Glubke, Dzung Nguyen and all the IMA staff who are responsible for the IMA's first rate operation. Special thanks to Patricia V. Brick for her professionalism in the production of these two volumes.

The Workshop on Emerging and Reemerging Diseases and the preparation of these volumes were partially supported by NSF and NIH grants to IMA. We want to thank these agencies for their support although we must re-state that the views and research presented in these volumes are the direct responsibility of the authors and the editorial group, that is, they do not represent the views of the funding agencies or the IMA.

Carlos Castillo-Chavez (Cornell University)

Sally Blower (University of California at Los Angeles)

Pauline van den Driessche (University of Victoria)

Denise Kirschner (University of Michigan)

Abdul-Aziz Yakubu (Howard University)

CONTENTS

Foreword	v
Preface.....	vii
New directions in the mathematics of infectious disease	1
<i>Simon A. Levin</i>	
Fred Brauer: The man and his mathematics	7
<i>Christopher M. Kribs-Zaleta</i>	
Kenneth L. Cooke: Researcher, educator par excellence	21
<i>P. van den Driessche</i>	
Maximal prevalence and the basic reproduction number in simple epidemics.....	31
<i>L. Esteva and K.P. Hadeler</i>	
The transition through stages with arbitrary length distributions, and applications in epidemics.....	45
<i>Horst R. Thieme</i>	
Measles outbreaks are not chaotic	85
<i>Ingemar Nåsell</i>	
Epidemics among a population of households	115
<i>Frank G. Ball and Owen D. Lyne</i>	
Infection transmission dynamics and vaccination program effectiveness as a function of vaccine effects in individuals.....	143
<i>Carl P. Simon and James S. Koopman</i>	
The influence of different forms of cross-protective immunity on the population dynamics of antigenically diverse pathogens	157
<i>Neil Ferguson and Viggo Andreasen</i>	
Dynamics of multiple strains of infectious agents coupled by cross-immunity: A comparison of models.....	171
<i>M. Gabriela M. Gomes and Graham F. Medley</i>	

Virulence evolution in macro-parasites 193
Andrea Pugliese

Mathematical models for schistosomiasis with delays
and multiple definitive hosts 215
Jianhong Wu and Zhilan Feng

Infectious disease models with chronological age
structure and epidemiological age structure 231
Fred Brauer

Effects of genetic heterogeneity on HIV transmission
in homosexual populations 245
Shu-Fang Hsu Schmitz

Age-structured core group model and its impact on
STD dynamics 261
Carlos Castillo-Chavez and Wenzhang Huang

Global dynamics of tuberculosis models with
density dependent demography 275
*Baojun Song, Carlos Castillo-Chavez,
and Juan P. Aparicio*

Global stability in some SEIR epidemic models 295
Michael Y. Li and Liancheng Wang

The global stability analysis for an SIS model with
age and infection age structures 313
Yicang Zhou, Baojun Song, and Zhien Ma

Endemic threshold and stability in an
evolutionary epidemic model 337
Hisashi Inaba

Epilogue 361

List of tutorial/workshop participants 363

IMA volume 125 contents: Mathematical approaches
for emerging and reemerging infectious diseases:
an introduction 367