Front cover figure: Adhesion of bacteria to substrata is a remarkably specific phenomenon. The scanning electron micrograph on the cover illustrates type 1 fimbria-mediated adhesion of uropathogenic *Escherichia coli* to murine bladder epithelial cells. An epithelial cell near the center of the field is covered by hundreds of *E. coli* cells, while the five surrounding cells are virtually devoid of adherent bacteria. To date, there is no molecular explanation for this mosaic pattern of *E. coli* adhesion. Both commensal and pathoadaptive alleles of the adhesin subunit of type 1 fimbriae, FimH, can be found within the overall *E. coli* population. The strain illustrated in this micrograph expresses a pathoadaptive allele of FimH that is typical of uropathogenic *E. coli*. Strains expressing commensal alleles of FimH adhere in extremely small numbers to uroepithelial cells. See chapters 4 and 6 for more information. Micrograph courtesy of D. L. Hasty (University of Tennessee and Veterans Administration Medical Center, Memphis, Tenn.), E. V. Sokurenko (University of Washington, Seattle, Wash.), and Lou Boykins (University of Memphis Integrated Microscopy Center, Memphis, Tenn.). Tim Higgins (Illustrator, University of Tennessee Health Science Center, Memphis) contributed to the cover design.

Back cover figure: Surface view of the FimH molecule (purple), crystallized in the presence of the FimC chaperone (yellow) and a molecule of C-HEGA (green) occupying the mannos-binding site of the lectin. The figure was created with the PyMOL molecular graphics system program of W. L. Delano (http://www.pymol.org) and is provided courtesy of Stefan Knight, Department of Molecular Biology, Swedish University of Agricultural Sciences, Uppsala Biomedical Centre, Uppsala, Sweden.

Copyright © 2003 ASM Press
American Society for Microbiology
1752 N St., N.W.
Washington, DC 20036-2904

Library of Congress Cataloging-in-Publication Data

Ofek, Itzhak.
Bacterial adhesion to animal cells and tissues / Itzhak Ofek, David L.
Hasty, and Ron J. Doyle.
p. ; cm.
Updates: Bacterial adhesion to cells and tissues / Itzhak Ofek and Ronald J. Doyle. 1994. Includes bibliographical references and index.
ISBN 1-55581-263-5 (hardcover)
IV. Title.
QR96.8.O45 2003
616’.014—dc21
2003005915

All Rights Reserved
Printed in the United States of America

Address editorial correspondence to ASM Press, 1752 N St., N.W., Washington, DC 20036-2904, U.S.A.

Send orders to: ASM Press, P.O. Box 605, Herndon, VA 20172, U.S.A.
Phone: 800-546-2416; 703-661-1593
Fax: 703-661-1501
E-mail: books@asmusa.org
Online: www.asmpress.org
We dedicate this volume to our coauthor and great friend, Ron Doyle. We first became aware that Ron was suffering from amyotrophic lateral sclerosis (Lou Gehrig’s disease) in the fall of 2000, when he told us of some weakness in his right arm. The rapidity with which he succumbed to this terrible disease makes us wish we could change our field of research to search for a treatment or cure. The grace with which he accepted his fate makes us wish to have a fraction of his strength of character. With the untimely death of Ron Doyle on 18 January 2002, microbiology lost one of its leaders and we, and many, many others, lost a valued friend and colleague. We miss him tremendously.

Ron was born in Calvert City, Ky., and attended Northeast Louisiana University, Monroe, La., where he studied chemistry and played basketball. He obtained his Ph.D. in microbiology at the University of Louisville Medical School in 1967. He then moved to Roswell Park Institute in Buffalo, N.Y., for postdoctoral studies in protein chemistry. In 1969 he moved back to Kentucky and started his 33-year career in the Department of Microbiology at the University of Louisville, where he became full professor in 1979. During Ron’s career in Louisville, he was heavily involved in teaching assignments and directed a very active research laboratory. Ron also served in a variety of administrative posts, including associate dean for research in the University of Louisville School of Dentistry, a Sigma Xi National Lecturer, an American Society for Microbiology division chair, and a Canadian Society of Microbiology section chair. He was also elected to membership in ASM’s prestigious American Academy of Microbiology. To say that Ron liked to travel is a major understatement. He traveled all over the world, becoming involved in international research and teaching projects. He lectured widely throughout the world and participated in joint research projects with scientists in various countries. He was an honorary member of the Israeli Society of Microbiology and the Romanian Academy of Medicine.

Although Ron traveled to many different countries around the world, everyone who knew him could attest to the fact that Israel was his favorite. In
fact, his determination to write this book on bacterial adhesion, and the 1994 Ofek–Doyle book, was very possibly because it gave him a good excuse to return to Israel year after year. His first contact with Israel was during a 1984 sabbatical at the Weizmann Institute of Science. This initial visit led to continuing collaborations with scientists at the Weizmann Institute, Tel Aviv University, the University of Jerusalem, and Bar-Ilan University. Several of the collaborative projects were supported by joint U.S.-Israel grants. Ron also initiated research projects with scientists from the Arab community of Israel, focusing on rapid diagnosis of mycobacteria, funded by a grant from the Israeli Ministry of Health. Ron went to Israel to write and work and experience its cultures and its history even during times when almost no one else would come.

Ron’s early studies focused on cell wall constituents, particularly those of gram-positive bacteria, such as peptidoglycan, teichoic acid, and teichuronic acid. His work greatly advanced our knowledge about the function of these constituents in cell growth and division. His interest in bacterial adhesion originated in the late 1960s, when it became clear that bacterial lectins were involved in the mechanisms used by oral bacteria to cause disease. His interest in this subject was undoubtedly influenced by his earlier studies of lectin-sugar interactions. Ron was an early proponent of using mathematical approaches developed for ligand-receptor interactions for studying bacterial attachment to substrata. Thanks to his contributions, adhesion data can now be analyzed using Scatchard, Hill, and related plots to estimate the affinity, cooperativity, and other parameters of the adhesion. Ron was also one of the first to point out the importance of hydrophobicity in the adhesion process. This was a concept initially dismissed as irrelevant by many researchers in the field, but Ron stood his ground and has long since been vindicated, as the importance of the hydrophobic effect became widely accepted. In more recent years, Ron collaborated with scientists in Mexico, Israel, Romania, and Bulgaria to develop rapid diagnostic tools involving lectin recognition of microbial surfaces. Ron also worked on antiadhesion therapies for bacterial infections. As a variation on this theme, he found that fluoride, at concentrations present in fluoridated tap water, suppresses the ability of streptococci to express adhesins and other virulence factors.

These are a few examples of Ron’s contributions to the field of microbiology, many of which have had a marked impact on the field. Ron’s legacy includes some 200 primary publications and many reviews and books. His books dealt with a great diversity of subjects, including a number of different areas of current microbiological research and also with the far-reaching consequences of microbiology on culture and history. Family, friends, and colleagues all miss Ron, as do the many dozens of scientists and students from around the world who were the beneficiaries of his generosity. Microbiology has lost a pioneering spirit, and we have lost a very dear friend.

ITZHAK OFEK AND DAVID HASTY
September 2002
It will be clear from our Dedication that the preface to this book is being written one year after the death of Ron Doyle. Ron played an instrumental role in much of the writing of the text. Even throughout 2001, the year in which he was most afflicted by the debilitating effects of amyotrophic lateral sclerosis, he worked with us on various sections of this book. On several occasions, we visited Ron in Louisville or he visited us during Ofek’s sabbatical in Memphis. He had even planned one final trip to Israel for the fall of 2001 to continue working on the book, as well as to visit the country he loved. He continued to play a very important role in writing this book and remained much more active than we had any right to expect, almost until the end of his life.

This text represents an effort to update a 1994 text, *Bacterial Adhesion to Cells and Tissues*, by Ofek and Doyle. The literature surveyed for the previous publication ended on 1 January 1992. The literature surveyed in this volume ended, with some exceptions, on 1 January 2002. Thus, the period covered was a full decade of very active investigation in the field of bacterial adhesion. Many achievements were made over this 10-year period, as evidenced from the many publications cited. We have endeavored to cover as many important issues as possible, but a complete overview of the field became impossible. Although a wholehearted effort was made to review all of the pertinent publications, undoubtedly there were some that escaped our attention, and we apologize in advance to the investigators whose work we did not include. The chapters cover general principles, methodology, characteristics of target cells and tissues, characteristics of bacterial surfaces and the regulation of surface protein expression and biogenesis, and several common themes that emerged during the last decade or two and are under very active investigation. The final chapter compiles, primarily in table form, a list all of the pathogenic bacterial species that were tested for their ability to adhere, the test substrata used, and the adhesins involved in the cases where they were known. It will only take a cursory glance to see which species have received the most attention.
and to indicate, perhaps, which species offer an opportunity for more active investigation.

We express our gratitude to a number of people who have contributed to our project in various ways. Large parts of this book were written in countries other than the United States and Israel due to the hospitality and inspiration of many of our international colleagues, and our very special thanks go to them: Giuseppe Teti and colleagues at the University of Messina, Messina, Italy; Karen Krogfelt at the Statens Serum Institut, Copenhagen, Denmark; Hany Sahly at the University of Kiel, Kiel, Germany; and Thomas Hartung at the University of Konstanz, Konstanz, Germany. The hospitality of Erika Crouch, Washington University Medical School, St. Louis, Mo., is also gratefully acknowledged. We are grateful to Kelly Cowan (Department of Microbiology, Miami University, Oxford, Ohio) for writing the Mathematical Analyses section of chapter 2. Naomi Balaban (Department of Human Microbiology, Tel Aviv University, Tel Aviv, Israel), Kevin McIver (Department of Microbiology and Immunology, University of Texas, Southwestern, Dallas, Tex.), and Mark Schembri (Department of Microbiology, Technical University of Denmark, Lyngby, Denmark) were kind enough to read and offer advice on various sections of chapter 4. Evgeni V. Sokurenko provided help with the discussion of probiotics as antiadhesion therapeutic agents in chapter 11. A special debt of gratitude goes to Memphis coworkers, especially Loretta Hatmaker, Tim Higgins, Susan Price, and Linda Snyder, for the variety of important ways in which they helped.

Finally, we acknowledge granting agencies (NIH, Department of Veterans Affairs, U.S.-Israel Bi-National Science Foundation, Ocean Spray Cranberry Co.) for funding work on mechanisms of bacterial adhesion and antiadhesion-based therapy in our laboratories.

ITZHAK OFEK AND DAVID HASTY

January 2003
CONTENTS

Preface • ix

Chapter 1. Basic Concepts in Bacterial Adhesion • 1
Chapter 2. Methodological Approaches to Analysis of Adhesins and Adhesion • 19
Chapter 3. Target Tissues for Bacterial Adhesion • 43
Chapter 4. Adhesins as Bacterial Cell Surface Structures: General Concepts of Structure, Biogenesis, and Regulation • 63
Chapter 5. Emerging Concepts in Bacterial Adhesion and Its Consequences • 97
Chapter 6. Diversification of Receptor Specificities and Its Biological Consequences • 101
Chapter 7. Entry of Bacteria into Nonphagocytic Cells • 113
Chapter 8. Postadhesion Events Induced in Nonphagocytic Cells • 127
Chapter 9. Adhesion-Dependent Upregulation of Bacterial Genes • 143
Chapter 10. Role of Adhesion in Biofilm Formation • 147
Chapter 11. Antiadhesion Therapy • 157
Chapter 12. Adhesins, Receptors, and Target Substrata Involved in the Adhesion of Pathogenic Bacteria to Host Cells and Tissues • 177

Index • 407
A

Accessory gene regulator cascade, regulation system of S. aureus, 71, 74

Acetobacter, 182

N-Acetylglucosamine, 64

N-Acetylmuramic acid, 68

Acinetobacter baumannii, 182

Actinobacillus actinomyctetus, 182

Actinobacillus pleuropneumoniae, 182

Actinomyces, binding to sugars on streptococcal surfaces and, 152

Actinomyces israelii, 182

Actinomyces naeslundii, 182

Actinomyces odontolyticus, 182

Actinomyces pleuropneumoniae, 182

Actinomyces pyogenes, 182

Actinomyces serovar, 182

Actinomyces viscosus, 182

Adhesin(s), 1

allellic variation of, 105

anchoring on cell surfaces, mechanisms for, 65, 66

and adhesion, analysis of, methodological approaches to, 19–42

as bacterial cell surface structures, 63–96

cognate receptors of, 4–5

fibronectin binding protein, 127

FimH, conformational changes in, K. pneumoniae and E. coli and, 107–109

E. coli and, 107, 109

gram-negative, regulation of expression of, 85–90

gram-positive, regulation of expression of, 71–77

identification of, genetic and biochemical techniques for, 35–36

in experimental infections, 37

in natural infections, 36–37

in Neisseria, variation of, 103

lectins as, 5–8

classification of, 6

multiple, 11–12

bacterial clones possessing, 99, 106

expression of, 12

nature of, 4–5

new, horizontal acquisition of, 102–105

of gram-positive bacteria, anchoring of, 65, 66

on bacterial surfaces, lectins as, 98–99

pathogenicity islands encoding, 102–103

phenotypic expression of, 12

production of, 11

proteinaceous, antigenic variability and, 159–160

receptor specificity of, variations in, 101, 102

type 1 and P, expressed by Escherichia coli, effects of, 106–107

Adhesin-receptor interactions, 4–5

Adhesin-receptor relationships, complexities of, 10–11

Adhesion, adhesins and, analysis of, methodological approaches to, 19–42

and internalization, differentiation between, 33–35

as energy-dependent event, 1

basic concepts in, 1–17

biological functions of, other than mediation of attachment, 97–98

cooperative, 3

dietary inhibitors of, 164, 166–169

electrical double layer and, 1, 3

emerging concepts in, biological consequences of, 97–100, 106–110

flow cytometry to study, 24, 25

inhibition of, saccharide as receptor analog for, 160–161

sublethal concentrations of antibiotics for, 164–165

interaction with cells of immune system, 99
mechanisms of, terms for, 19
milestones in—1900–2001, 2
of pathogenic bacteria to host cells and tissues, 177–405
abbreviations associated with, 178
process of, 1–4
quantification of, 29, 31
quantitative data on, mathematical analyses of, 31–33
relationship of, to infectivity, 12
reversible step of, 4
role in biofilm formation, 147–156
role in infection, 12–13
steps in, 2–4, 138
studies from 1992 to 2002, 177
pathogens, adhesins, receptors, and target substrata in, 179–207
studies of, focus of, 177
history of, 1
target tissues for, 43–62
themes in field of, 98
to animate and inanimate surfaces, 24–30
two-step kinetic model of, 3, 4
Adhesion analog(s), for inhibition of adhesion, 161
in antiadhesion therapy, 163–164
Adhesion-based vaccine, 158–160
Adhesion tests, of host cells or tissue components, 177–178
of materials of prosthetic devices or indwelling medical equipment, 177–178
*Aeromonas*, 183
*Aeromonas caviae*, 183
*Aeromonas hydrophilia*, 183
*Aeromonas salmonicida*, 183
*Aeromonas sobria*, 183
*Aeromonas trota*, 183
*Aeromonas veronii*, 183
Agarose beads, to fractionate proteins, 22
Agglutination reactions, 23–24
as secondary effect of adhesion, 24
target cells and particles used in, 23
Agglutination tests, nonerythrocyte particles in, 23–24
Aggrecan, 55
*Agrobacterium*, 183
airS gene, upregulation of, uropathogenic *E. coli* and, 143, 144
*Alcaligenes*, 183
Allelic variation, of adhesins, 105
*Alteromonas*, 183
*Anaplasma marginale*, 183
Animal cells, bacterial attachment to, studies of, 26–30
quantitation of adhesion to, 28–30
Antiadhesions agents, actions of, 157
disadvantages of, 157
effect of, on resistant bacteria, 157, 159
host-derived, in innate immunity, 169–170
potential of, 157
probiotics as, 165–166
receptor analogs of, 160–163
Antiadhesion therapy, 157–176
adhesion analogs in, 163–164
adhesion studies and, 20–23
future of, 170
plant lectins and, 167
*Antibiotics*, effects of, on resistant bacteria, 157, 158
β-lactam, release of muramyl peptides and, 67
treatment of *E. coli* with, 164–165
sublethal concentrations of, for inhibition of adhesion, 164–165
*Antibodies*, fluorescein-labeled, to assess extracellular and internalized bacteria, 34
*Apoporulin*, 56
*Anarobacterium pyogenes*, 183
*Arcobacter*, 183
*Arthrobacter*, 183
Atomic force microscopy, to analyze living tissues, 28–30

**B**

*Bacillus cereus*, 183
*Bacillus piliformis*, 183
*Bacillus subtilis*, 183
Bacteria, adaptation to deleterious agents, 157
adherent, quantification of, methods for, 28, 29
separation from nonadherent, methods for, 24, 25, 26
shear forces and, 24
attachment of, to animal cells, studies of, 26–30
carbohydrates as attachment sites for, 6
endogenous, 187
entry of, into nonphagocytic cells, 113–126
invasome mechanism of, 116–117, 119
target mechanism of, 115–118
zipper mechanism of, 115, 116–117
extracellular, able to enter nonphagocytic cells, 113, 114
extracellularly bound and internalized, methods to distinguish, 33–34, 36
gram-negative, cell surfaces of, 63, 65
cell wall and membranes of, general characteristics of, 77–79
fimbriae of, 78
intercalated proteins of, 78
outer membrane proteins of, 78
phospholipid-lipopolysaccharide-protein bilayer of, 77–78
polysaccharide capsular material of, 79
gram-positive, adhesins of, anchoring of, 65, 66
cell surfaces of, 63, 64
cell wall of, 65–67
growth of, in nonphagocytic cells, 114
inhibition of adhesion of, cranberry extracts and, 164, 167–169
interaction of glycoconjugates and saccharides for
milk in, 166–167
intracellular, entering nonphagocytic cells, 114
partitioning of, 19–23
probiotic, see Probiotics
radiolabeled, to quantify adherent bacteria, 29
resistant, effect of antiadhesion agents on, 157, 159
effects of antibiotics on, 157, 158
uptake of, trigger mechanism of, 115–117
zipper mechanism of, 115, 116
Bacterial adhesion, see Adhesion
Bacterial cell surface structures, adhesins as, 63–96
Bacterial clones, with multiple adhesins, 99, 106
Bacterial infection, prevention in vivo, carbohydrates in,
162
Bacterium-substratum interactions, biofilm physiology
and, 147
Bacteroids, 184
Bacteroides distasonis, 183
Bacteroides forsythus, 183
Bacteroides fragilis, 183
Bacteroides merdae, 184
Bacteroides multiciacidus, 184
Bacteroides ovatus, 184
Bacteroides stercoris, 184
Bacteroides thetaiotaomicron, 184
Bacteroides vulgatus, 184
Bartonella, nonhemolytic, within erythrocytes, 122
Bartonella bacilliformis, invasome mechanism of entry of,
119, 184
Bartonella henselae, invasome mechanism of entry of,
119, 120, 184
Bartonella quintana, 184
Bifidobacterium adolescentis, 184
Bifidobacterium breve, 184
Bifidobacterium infantis, 184
Bifidobacterium lactis, 184
Bifidobacterium suis, 184
Binding, kinetics of, for monitoring of quantitative
adhesion, 31–33
Biochemical techniques, for identification of adhesins,
35–36
Biofilm(s), bacteria participating in, advantages gained
by, 150
composition of, 147
dental, saliva and, 152
dental ecology of microbiota of, 150–152
description of, 147
development on biomaterials, infectious diseases and,
153–154
formation of, factors modulating, 153, 154
mechanism of, 147–149
quorum sensing and, 149–150
regulation of, 149–150
role of adhesion in, 147–156
of dental plaque, 150–153
physiology of, bacterium-substratum interactions and,
147
Biomaterials, adhesion to, 153
biofilm development on, infectious diseases and,
153–154
Biomechanical measurements, to quantify adherent bac-
teria, 29
Bordetella, invasome therapy and, 160
Bordetella avium, 185
Bordetella bronchiseptica, 185
Bordetella parapertussis, 185
Bordetella pertussis, 10–11
cooperativity mechanism and, 138, 185
Brucella abortus, 185
Brucella garinii, 185
Brucella henselae, 185
Brucella japonica, 185
Brucella tenticatae, 185
Bridging molecule, in activation of cytoskeletal system,
127, 128
Bsalleva abortus, invasome mechanism of entry of, 119, 185
Burkholderia pseudomallei, 185
Burkholderia (Pseudomonas) cepaia, 185
C
Cadherins, 53
Campylobacter coli, 185
Campylobacter curvus, 185
Campylobacter fetus, 186
Campylobacter jejuni, 186
Campylobacter rectus, 186
Campylobacter upsaliensis, 186
Capsule synthesis regulator/capsule synthesis regulator
sensor operon, 77
Carbohydrates, as attachment sites for bacteria, 6
in prevention of bacterial infection in vivo, 162
Caveolae, 50
Caveolin, 50
CD48 glycolipoprotein, 50
Cell coat, 55
Cell surface(s), anchoring adhesins on, mechanisms for,
65, 66
hydrophobicity of, definition of, 19–20
of gram-negative bacterium, 63, 65
of gram-positive bacterium, 63, 64
receptors on, 57–58, 98–99
structures of, adhesins as, 63–96
Cell wall(s), gram-positive surface proteins anchored to,
67–71
lipoteichoic acid membrane of, 67, 68
of gram-negative bacteria, general characteristics of,
77–79
of gram-positive bacteria, 65–67
Cellular membrane, asymmetry of, 49
components of, as receptors for adhesins, 50
organizational features of, 47–49
general features of, 48, 49–51
glycolipids of, 48, 50
glycoproteins of, 51–52
gram-negative bacteria, general characteristics of, 77–79
integral constituents of, 49–53
peripheral, constituents of, 53–55
polarization in, 49
Chlamydia pneumoniae, 186
Chlamydia psittaci, 186
Chlamydia trachomatis, nonphagocytic cells and, 114, 186
Chromatography, thin-layer, for identification of fimbrial glycolipid receptors, 27, 28
Citrobacter diversus, 186
Citrobacter freundii, 186
Clostridium difficile, 186
Clostridium perfringens, 186
Coaggregation, dental plaque and, 24
Cold-insoluble globulin of plasma, 54
Collagen-proteoglycan-hyaluronic acid complex, 55
Collagens, 53–54
Contact angle technique, to measure hydrophobicity, 22
Corynebacterium, 187
Corynebacterium diphtheriae, 186
Corynebacterium jeikeium, 186
Corynebacterium matruchotii, 187
Corynebacterium parvum, 187
Corynebacterium urealyticum, 187
Coryneforms, 187
Cowella burnetii, 187
Cranberry extracts, inhibition of adhesion of bacteria and, 164, 167–169
Cystic fibrosis, P. aeruginosa and, 122
Cytokines, proinflammatory, release of, by nonprofessional phagocytes, 36
Cytoskeletal system, activation by pathogens, “bridging” mechanisms of, 127, 128
activation by secretion-dependent pedestal formation, 129–131
activation of, type III secretion apparatus-mediated, 129–130
secretory system–dependent transcriptional responses of, 131–138

Dental plaque, 24
as complex multispecies biofilm, 150
biofilm of, 150–153
Deoxyadenosine methylase, 87
Desfominomile tiedei, 187
Desfordinobio, 187
Dextran(s), 150
polyethylene glycol and, partitioning system using, 20–21
Dichelobacter nodosus, 187
Diet, inhibitors of adhesion in, 164, 166–169
DVLO theory, 1
Edwardsiella ictaluri, 187
Edwardsiella tarda, 187
Effector molecules, activation and inhibition of transcription by, 131, 134
translocation via type III or type IV secretion apparatus, 134
Ehrlichia chaffeensis, 187
Ehrlichia risticii, 187
Enterocytes, absorptive, in intestinal mucosa, 45, 46
basic components of, 43, 45
Enzyme-linked immunosorbent assay (ELISA), for quantification of bacteria, 22, 29, 31
to assess extracellular and internalized bacteria, 34
Epithelial cells, 43
intestinal, basic components of, 43, 45
molecular organization of, 45, 47, 48, 49
Epithelium, basic characteristics of, 43, 44
stratified and simple, 43, 44
surface of, basic characteristics of, 46, 47
Environia harapentii, 188
Environia chrysochanthii, 188
Escherichia coli, and K. pneumoniae, conformational changes in FimH adhesins and, 107–109
antiadhesion therapy and, 160
bearing K99 fimbriae, binding to glycolipids, 58
enteropathogenic, secretion–dependent pedestal formation and, 131, 132, 133
Tir, and actin linkage, 134
entry into nonphagocytic cells and, 121
FimH adhesins and, 107, 109
in intestinal mucosa, scanning electron microscopy in, 28, 30
new adhesins for, techniques for identification of, 35
987P type fimbriae of, 79–80, 82
purified type 1 fimbriae of, 79, 80, 88
recombinant, type 1 fimbriae of, 78
studies of adhesion from 1992–2002, 177, 179–181
treatment with β-lactam antibiotics, 164–165
type 1 and P fimbrial adhesins expressed by, effects of, 106–107
uropathogenic, adhesion in gene activation and, 143,
Escherichia coli receptors, sodium dodecyl sulfate-polyacrylamide gel electrophoresis and, 27
Extracellular pathogens, entering nonphagocytic cells, 119–122

F
Fibronectin(s), 54
binding sites, 9
on animal cells, 9
Fibronectin binding protein, 3–4
Fibronectin binding protein adhesins, 127
Fimbriae, 1
adhesions of, 7, 8, 102
as trigger for gene expression within the cell, 90
biogenesis of, 80–90
classification of, 79–80
curl of, 80, 83
gram-negative, biogenesis of, 84
phase variation of expression of, 86, 89
987P type, E. coli, 79–80, 82
of gram-negative bacteria, 78
purified type 1, 79, 80, 88
E. coli cell, 79, 81
type 1, of recombinant E. coli, 78
regulation of, 86, 89–90
type 1 and P, adhesins, 86, 89
expressed by E. coli, 106–107
expression and biogenesis of, 83–85, 86, 87, 88
type IV, 80, 84
type P, PapG lectins of, receptors for, 110
regulation of, 86–89
Flavobacterium columnare, 188
Flavobacterium meningosepticum, 188
Flow cytometry, to study adhesion, 24, 25
Fluorescein-labeled antibodies, to assess extracellular and internalized bacteria, 34
Fluorescence, to quantify adherent bacteria, 29
Focal adhesion kinase, 127
Fusarium oxysporum, 188
Fusobacterium necrophorum, 188
Fusobacterium nucleatum, 11, 188

G
Gardnerella vaginalis, 188
GATC sequence, Lrp binding and, 87–89
Genes, bacterial, adhesion-dependent upregulation of, 143–146
rearrangement of, receptor specificity and, 103–105
Genetic techniques, for identification of adhesins, 35–36
Glucans, 150
Glucosyltransferase, adhesion of oral streptococci on teeth and, 151
Glycocalyx, 45, 46, 53
Glycoconjugates, and saccharides, from milk, interaction with bacteria, 166–167
Glycolipids receptors, fimbrial, thin-layer chromatography for identification of, 27, 28
Glycolipids, carbohydrate residues of, cellular changes in, 57
E. coli K99 fimbriae binding to, 58
of cellular membrane, 48, 50
Glycolipoprotein, CD48, 50
N-Glycolyneuraminic acid, 58
Glycoproteins, carbohydrate residues of, cellular changes in, 57
isoreceptor, 10, 11
mucin, 57
of cell coat, 55
of cellular membrane, 51–52
Glycosphingolipids, 49–50
Glycosylphosphatidylinositol lipid anchor, 48
Glypicans, 52
Goblet cells, mucus secreted by, 46
Gordona, 188
Green fluorescent proteins, to probe for and assess bacteria, 34–35
Growth assay, to quantify adherent bacteria, 29
Gut-associated lymphoid tissue, 46

H
Haemophilus aphrophilus, 188
Haemophilus ducreyi, 188
Haemophilus influenzae, antiadhesion therapy and, 162, 163, 189
Haemophilus paragallinarum, 189
Haemophilus parainfluenzae, 189
Haemophilus parasuis, 189
Haemophilus somnus, 189
Hafnia alvei, 189
Halomonas marina, 189
Helicobacter acinonyx, 189
Helicobacter felis, 189
Helicobacter mustelae, 189
Helicobacter nemestrinae, 189
Helicobacter pylori, adhesins and receptors for, steps for identification of, 35, 36, 190
secretion-dependent pedestal formation and, 131
translocation via type IV system, 134
Hemagglutination, 1
bacterium-induced, 23
Hemagglutinin, 10–11
Heparan sulfate proteoglycan receptors, bacteria binding to, 52
Heparan sulfate proteoglycans, 52
Hexadecane, interaction of hydrophobic and hydrophilic bacteria with, 20, 21
Hyaluronic acid, in antiadhesion therapy, 163–164
Hydrophobic effect, 2
Hydrophobic molecule, 2
Hydrophobicity, cell surface, definition of, 19–20
Hydrophobin(s), 2
as bacterial adhesions, 10
Hydroxylapatite, saliva-coated, adhesion to, 3

I
Immune system, adhesion interaction with cells of, 99
Immunity, active antiadhesion, 158
innate, host-derived antiadhesins in, 169–170
passive antiadhesion, 158–159
Immunofluorescence, to quantify adherent bacteria, 29
Infection(s), bacterial, prevention in vivo, carbohydrates in, 162
biofilm development on biomaterials and, 153–154
experimental, adhesins in, 37
molecules in adhesion and, 177
natural, adhesins in, 36–37
and experimental, study of adhesion process during, 36–37
outcome of, changes in adhesin receptor specificity and, 58
relationship of adhesion to, 12
role of adhesion in, 12–13
susceptibility to, secretor and nonsecretor status as influence on, 170
Integrins, 50, 51–52
Intealin A, 115, 127
Intealin B, 115
Internalization, and adhesion, differentiation between, 33–35
Intestinal mucosa, cell types in, 46
mucus in, 46
structure of, 46
Intracellular pathogens, facultative, entering nonphagocytic cells, 115
obligate, entering nonphagocytic cells, 114
Invasin, 115, 127
Isoreceptors, 10

K
Kinetic method, for monitoring of quantitative adhesion, 31–33
Klebsiella, 190
Klebsiella oxytoca, 190
Klebsiella ozaenae, 190
Klebsiella pneumoniae, and E. coli, conformational changes in FimH adhesins and, 107–109, 190
capsular material of, 79
sites of infection caused by, 122

L
β-Lactam antibiotics, release of muramyl peptides and, 67
treatment of E. coli with, 164–165
Lactobacillus, in study of probiotic activity, 165, 166, 192
Lactobacillus acidophilus, 190
Lactobacillus brevis, 191
Lactobacillus casei, 191
Lactobacillus crispatus, 191
Lactobacillus delbrueckii, 191
Lactobacillus fermentum, 191
Lactobacillus gasseri, 191
Lactobacillus GG, 191
Lactobacillus jensenii, 191
Lactobacillus leichmannii, 191
Lactobacillus oris, 191
Lactobacillus paraaceti, 191
Lactobacillus plantarum, 191
Lactobacillus ruminis, 191
Lactobacillus salivarius, 191
Lactococcus lactis, 192
Lamina propria, 43–44, 45
Laminins, 54–55
Langmuir isotherm, in analysis of quantitative adhesion, 31
Lectin(s), as adhesins, 5–8
classification of, 6
as adhesins on bacterial surfaces, 98–99
as receptors on animal cells, 98–99
bacterial, adhesins of, 7
binding with carbohydrate structures, 4, 5
fimbrial, sugar specificities of, 102, 106, 110
intracellular, dying cells of Pseudomonas aeruginosa and, 149–150
PapG, of P fimbiae, receptors for, 110
plant, antiallusion therapy and, 167
Legionella haemophilae, 192
Legionella micdadei, 192
Legionella pneumophila, adhesins and receptors for, steps for identification of, 35, 36, 192
Leptospira interrogans, 192
Leptotrichia buccalis, 192
LETS protein, 54
Leukocytes, polymorphonuclear, lipoteichoic binding to, 50, 51
Light microscopy, to quantify adherent bacteria, 29
Lipid anchor, glycosylphosphatidylinositol, 48
Lipid “rafts,” 49–50
Lipids, membrane, 47
Lipoplyosaccharides, bacterial, as adhesins, 8–9
Lipoteichoic acid, 2, 3, 20
binding to polymorphonuclear leukocytes, 50, 51
in antiadhesion therapy, 163
membrane, in cell wall, 67, 68
proinflammatory properties of, 97–98
Listeria innocua, 192
Listeria ivanovii, 192
Listeria monocytogenes, 192
zipper mechanism of, uptake and, 115, 116–117
LPXTG motif, of wall-anchored proteins, 66, 67–69
Lung surfactant protein D, 9
Lymphoid tissue, gut-associated, 46
Lysozyme, 69

M

M cells, 46, 47
bacteria taken up by, 46, 47
M protein, 3–4
Macromolecules, host-derived, adhesion to, 153
Mannose, as receptor for enterobacteria, 161
Membrane lipids, 47
Metabolites, measurement of, to quantify adherent bacteria, 29
Mga, 75, 76
Microbial adhesion to hydrocarbons test (MATH test), 19, 20
experiments clarifying value of, 20–23
Milk, glycoconjugates, and saccharides from, and interaction with bacteria, 166–167
Mobiluncus curtisi, 192
Moraxella bovis, 192
Moraxella (Brahnamella) catarrhalis, 192
MSCRAMM, 53
Mucin glycoproteins, 57
Mucins, 55, 56
in adhesion, 27
Mucus, description of, 56
in adhesion, 27
in intestinal mucosa, 46
on mucosal surfaces, as host-derived antiadhesin, 169–170
Mucus blanket, 47, 55–57
Muramyl peptide(s), 66
release of, β-lactam antibiotics and, 67
Murein, 63
Mycobacterium avium (intracellulare), 192
Mycobacterium bovis (BCG), 192
Mycobacterium fortetum, 193
Mycobacterium leprae, 193
Mycobacterium smegmatis, 193
Mycobacterium tuberculosis, 193
Mycoplasma arthritidis, 193
Mycoplasma bovis, 193
Mycoplasma bovoculi, 193
Mycoplasma fermentans, 193
Mycoplasma flocculare, 193
Mycoplasma gallisepticum, 193
Mycoplasma genitalium, 193
Mycoplasma hominis, 193
Mycoplasma hypneumoniae, 193
Mycoplasma imitans, 194
Mycoplasma ivorae, 194
Mycoplasma mobile, 194
Mycoplasma ovipneumoniae, 194
Mycoplasma penetrans, 194

N

Neisseria, entry into nonphagocytic cells and, 119–121
variation of adhesins in, 103
Neisseria adhesins, Opa proteins and, 105
Neisseria gonorrhoeae, pilus biogenesis and, 103
pilus variation in, 104–105, 194
Neisseria lactamica, 194
Neisseria meningitidis, binding to epithelial cells, 143–144, 195
Neuraminidase, 69
Neutrophiles, 195
Nonerythrocyte particles, in bacterial agglutination tests, 23–24
Nonphagocytic cells, activation of, adhesion- and invasion-dependent mechanisms for, 134–138
adhesion and entry into, ligands and receptors in, 117
bacteria and, secretion system-dependent transcriptional responses and, 131, 134
bacteria with, secretion system-dependent transcriptional responses and, 131, 134
entry of bacteria into, 113–126
mechanisms of, 115–119
extracellular pathogens entering, 119–122
facultative intracellular pathogens entering, 115
obligate intracellular pathogens entering, 114
postadhesion events induced by, 127–142
Nonesecretor status, as influence on susceptibility to infection, 170

O

Ochrobactrum anthropi, 195
Oligosaccharides, N-linked, 56
Opa proteins, Neisseria adhesins and, 105
Outer membrane, 64

P

Pasteurella haemolytica, 195
Pasteurella multocida, 195
Pasteuria penetrans, 195
Pathogenicity islands, encoding adhesins, 102–103
Peptide(s), connecting, of S. aureus, 66
muramyl, 66
release of, β-lactam antibiotics and, 67
RNAIII-inhibiting, 73–75
Peptidoglycan(s), 63, 64
cell wall, anchorage of surface proteins to, 66
teichoic acid linked to, 67, 68
Peptostreptococcus micros, 195
Peptostreptococcus productus, 195
INDEX

Peyer’s patches, 46, 47
Phagocytic cells, internalization by, 33–34
Phosphatidylethanolamine, 47
Phospholipid-lipopolysaccharide-protein bilayer, of gram-negative bacteria, 77–78
PII proteins, outer membrane variation, 90
Pili, see Fimbriae
Plant extracts, dietary, in antiadhesion therapy, 167–169
Plant lectins, antiadhesion therapy and, 167
Polyethylene glycol, and dextran, partitioning system using, 20–21
Polymorphonuclear leukocytes, lipoteichoic binding to, 50, 51
Polysaccharides, bacterial, as adhesins, 8–9
Porphyromonas gingivalis, antiadhesion therapy and, 163, 195–196
Postadhesion signaling events, measurement of, 36
Prevotella dentica, 196
Prevotella intermedia (nigrescens), 196
Prevotella loeschii, 196
Prevotella melaninogenica, 196
Probiotics, actions of, 165
as antiadhesion agents, 165–166
Propionibacterium acnes, 196
Propionibacterium freudenreichii, 196
Protein(s), elastin binding surface, of S. aureus, 69
fibronectin-binding, 3–4
GPI-anchored, 48
gram-positive surface, anchorage to cell wall, 67–71
anchored to cell walls, 67–71
morphological appearance of, 69–71
green fluorescent, to probe for and assess bacteria, 34–35
leucine response regulatory, 87
M, 3–4
Opa, Neisseria adhesins and, 105
outer membrane, of gram-negative bacteria, 78
peripheral membrane, 48–49
PII, outer membrane variation, 90
wall-anchored, LPXTG motif of, 66, 67–69
wall-anchored surface, characteristics of, 67, 68
Protein-protein interactions, 9–10
Proteoglycans, 52
heparan sulfate, 52
receptors, bacteria binding to, 52
pericellular, 52
Proteus mirabilis, 196
Proteus mirgi, 196
Proteus vulgaris, 196
Providencia alcalifaciens, 196
Providencia rettgeri, 196
Providencia, 198
Pseudomonas aeruginosa, 9, 197
adhesin-dependent mechanism of, 138
antiadhesion therapy and, 162–163
cystic fibrosis and, 122
dying cells of, and intracellular lectins, 149–150
promotion of accretion and biofilm development by, 149
Pseudomonas (Burkholderia) cepacia, 197
Pseudomonas fluorescens, 197
Pseudomonas fragi, 198
Pseudomonas pseudoalteri, 198
Q
Quantitative techniques, in animal cells, 28–30
R
Radiolabeled bacteria, to quantify adherent bacteria, 29
RAMP-TRAP system, 73
Receptor analog(s), as antiadhesive agents, 160–163
saccharide as, for inhibition of adhesion, 160–161
Receptors, biological consequences of, 101–112
for P fimbriae of PapG lectins, 110
on cell surfaces, 57–58
lectins as, 98–99
specificities of, diversification of, 101–112
gene rearrangement and, 103–105
pronounced and subtle changes in, 101–102
Rhodococcus, 198
Rhodococcus equi, 198
RNAIII, 71–73
RNAIII-inhibiting peptide, 73–75
RofA-like protein (RALP) family, 75
Rothia dentariosa, 198
S
Saccharide(s), as receptor analog for inhibition of adhesion, 160–161
glycoconjugates and, from milk, interaction with bacteria, 166–167
in antiadhesion therapy of humans, 161, 162
specificities of bacterial lectin-adhesins, 7
Sacculus, 63, 68
Salmonella, 199
translocation via type III secretion system, 133
trigger mechanism of uptake and, 115–117
Salmonella enterica, fimbriae of, 83, 198
serovar Typhimurium, sugar specificity of, 109
Salmonella enterica serovar Abortusovis, 198
Salmonella enterica serovar Braenderup, 198
Salmonella enterica serovar California, 198
Salmonella enterica serovar Choleraesuis, 198
Salmonella enterica serovar Dublin, 198
Salmonella enterica serovar Enteritidis, 198
Salmonella enterica serovar Gallinarum, 198
Salmonella enterica serovar Pullorum, 198
Salmonella enterica serovar Typhi, 199
Salmonella enterica serovar Typhimurium, 199
SarA, 73
Scanning electron microscopy, for quantitative and qualitative information, 28, 29, 30
in E. coli in intestinal mucosa, 28, 30
Scatchard equation, in analysis of quantitative adhesion, 31
Secretor status, as influence on susceptibility to infection, 170
Selenomonas sputigena, 199
Serpulina pilosicoli, 199
Serratia, 199
Serratia liquefaciens, 199
Serratia marcescens, 199
Shear forces, adherent bacteria and, 24
Shewanella algae, 199
Shigella, effector molecules of, caspase-I activity and, 133
trigger mechanism of uptake and, 115, 116–118
Shigella boydii, 199
Shigella dysenteriae, 199
Shigella flexneri, 199
Shigella sonnei, 200
Sodium dodecyl sulfate–polyacrylamide gel electrophoresis, for analysis of E. coli receptors, 27
Sortase, 67–69
Sphinganin, inhibition of bacterial adhesion and, 169
Staphylococcus aureus, connecting peptide of, 66, 200–201
elastin binding surface proteins of, 69
polysaccharide intracellular adhesion of, 148–149
regulation of expression of virulence factors by, 71–75
studies of, increase in, 117
Staphylococcus capnii; 201
Staphylococcus epidermidis, polysaccharide intracellular adhesion of, 148–149
coagulase–negative, 201
Staphylococcus haemolyticus, 201
Staphylococcus hyicus, 201
Staphylococcus intermedius, 202
Staphylococcus lugdunensis, 202
Staphylococcus saprophyticus, 202
Streptococcal adhesion, 1
Streptococci, oral, morphologies of structures of, 69–71, 72–73
Streptococcus agalactiae, 202
Streptococcus anginosus, 202
Streptococcus anaerobius, siphinganin and, 169
Streptococcus bovis, 202
Streptococcus constellatus, 202
Streptococcus cricetus, 202
Streptococcus crista, 202
Streptococcus crispatus, 202
Streptococcus mutans, antiadhesion therapy and, 163, 203
Streptococcus oralis, 204
Streptococcus parasanguis, 204
Streptococcus pneumoniae, antiadhesion therapy and, 162, 163, 204
Streptococcus pyogenes, 5
Streptococcus salivarius, 205
Streptococcus sanguis, 205
Streptococcus suis, 205
Syndecans, 52
Sugar specificity(ies), lectin adhesins and, 106, 110
of fimbrial lectins, 102, 106, 110
of S. enterica serovar Typhimurium, 109
Syndecans, 52
Syntrophobacter wolinii, 202
Syntrophomonas wolfei, 205
Typhimurium, serovar, S. enterica, sugar specificity of, 109
Uracil, radiolabeled, to study adhesion and ingestion by phagocytic cells, 34
Ureaplasma urealyticum, 203

T
Teichoic acid, 63
linked to peptidoglycans of the cell wall, 67, 68
Teichuronic acid, 63
Tissue surfaces, animal, general structure of, 43–46
Treponema denticola, adhesion to epithelial cells, 138, 206
Treponema medium, 206
Treponema pallidum, 206
Treponema phagedenis, 206
Treponema socranskii, 206
Treponema vincentii, 206
Tropism, tissue, 1
Typhimurium, serovar, S. enterica, sugar specificity of, 109

U
Uracil, radiolabeled, to study adhesion and ingestion by phagocytic cells, 34
V

Vaccine, adhesion-based, 158–160
Veillonella atypica, 206
Viable counts, to quantify adherent bacteria, 29
Vibrio alginolyticus, 206
Vibrio cholerae, showing type IV fimbriae, 84, 206
Vibrio helveticus, 206
Vibrio mimicus, 206
Vibrio parahaemolyticus, 207
Vibrio vulnificus, adhesins and receptors for, steps for identification of, 35, 36, 207

Vitronectin, 55

Y

Yersinia, secretion system of, to translocate effector molecules, 131–133
zipper mechanism of, uptake and, 115, 116–117
Yersinia enterocolitica, 207
Yersinia pestis, 207
Yersinia pseudotuberculosis, binding to host cells, 145–146, 207
Yersinia ruckeri, 207

Yersinia pseudotuberculosis, 207