Ultraviolet Germicidal Irradiation Handbook

Wladyslaw Kowalski

Ultraviolet Germicidal Irradiation Handbook

UVGI for Air and Surface Disinfection

Springer

Wladyslaw Kowalski
Immune Building Systems, Inc.
575 Madison Ave.
New York, NY 10022
drkowalski@ibsix.com

ISBN 978-3-642-01998-2 e-ISBN 978-3-642-01999-9
DOI 10.1007/978-3-642-01999-9
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2009932132

© Springer-Verlag Berlin Heidelberg 2009
This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.
The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: WMXDesign GmbH, Heidelberg

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

I dedicate this book to Dr. Thomas Whittam and to his family. Tom passed away all too suddenly during the writing of this book. He was my mentor and tutor in the field of microbiology and genetics, and taught me laboratory techniques as well as inspiring me with the desire to achieve excellence. It had always seemed to me that scientists, unlike so many musicians, artists, writers, and actors, were always allowed to complete their greatest works, and so it is especially sad to see anyone leave this world when they are in the midst of doing great research and useful science, and when they had so much more to give.

Preface

This book is a comprehensive source for technical information regarding ultraviolet germicidal irradiation (UVGI) and its application to air and surface disinfection for the control of pathogens and allergens. The primary focus is on airborne microbes and surface contamination applications. Water-based applications are not addressed here except incidentally as they relate to air and surface microbes, since many adequate texts on water-based UV disinfection are available. All aspects of UVGI systems, including design methods, modeling, safety, installation, guidelines, and disinfection theory are addressed in sufficient detail that no additional sources need be consulted. It is hoped by the author that providing this information in one single volume will simplify the design and installation of UVGI systems, help guarantee effective performance of new systems, and facilitate their use on a wide scale for the purpose of improving human health and controlling epidemic disease. This book is organized to provide systematic coverage of all essential issues and will serve equally well as both a textbook and a handbook for general reference.

Any readers who find technical errors or omissions in this book may to send them to me at drkowalski@aerobiologicalengineering.com. Errata will be posted at http://www.aerobiologicalengineering.com/UVGI/errata.htm. All other correspondence should be sent to drkowalski@ibsix.com.

Acknowledgements

I gratefully acknowledge all those who assisted me in the research, preparation, and review of the chapters in this book, including William Bahnfleth, Steve Martin, Chuck Dunn, Jim Freihaut, Dave Witham, Ed Nardell, Richard Vincent, Mark Hernandez, Ana Nedeljkovic-Davidovic, Clive Beggs, Renzhou Chen, Normand Brais, Katja Auer, Warren Lynn, Mike Sasges, Bill Carey, Tatiana Koutchma, Forrest Fencl, Russ Briggs, Josephine Lau, Carlos Gomes, Fahmi Yigit, Herbert Silderhuis, Joe Ritorto, Merrill Ritter, Brad Hollander, Scott Prahl, Karl Linden, William Balch, Atanu Sengupta, M.D. Lechner, Ketan Sharma, Donald Milton, and especially Mary Clancy all the members of the IUVA Air Treatment Group who supported the UV Guidelines project, and also Linda Gowman, Jim Bolton and everyone in the International Ultraviolet Association who sponsored the UV Air Treatment Group. A special thanks goes to Ali Demirci and Raymond Schaefer for their contributions to the chapter on Pulsed UV Systems. I especially thank my parents, Stanley J. Kowalski and Maryla Kowalski, and my sister Victoria Chorpenning for their unwavering support and encouragement during these past few years as I recovered my health and returned to research.

Contents

1 Introduction 1
1.1 Ultraviolet Germicidal Irradiation (UVGI) 1
1.2 Brief History of Ultraviolet Disinfection 2
1.3 Units and Terminology 6
1.4 Air vs. Water Disinfection 8
1.5 Surface Disinfection 9
1.6 Air Disinfection 10
1.7 Air Disinfection Field Studies 10
1.8 Pathogens and Allergens 11
1.9 Current Research 12
1.10 UVGI and the Future of Disease Control 13
References 13

2 UVGI Disinfection Theory 17
2.1 Introduction 17
2.2 UV Inactivation 17
2.3 UV Absorption Spectra 25
2.4 UV Photoprotection 28
2.5 Covalent Bonding and Photon Interaction 31
2.6 UV Photoproducts 32
2.7 DNA Conformation 33
2.8 Photon Density and Single-Hit Concepts 35
2.9 Photochemistry of RNA Viruses 38
2.10 Photochemistry of DNA Viruses 39
2.11 Photochemistry of Bacteria 39
2.12 Photoreactivation 40
2.13 UV Scattering 42
References 47

3 Mathematical Modeling of UV Disinfection 51
3.1 Introduction 51
3.2 UV Disinfection Modeling 51
3.3 UV Exposure Dose (Fluence) 52

3.4 Single Stage Decay . . . 53
3.5 Two Stage Decay . . . 54
3.6 Shoulder Curves . . . 57
3.7 Two Stage Shoulder Curves . . . 58
3.8 Relative Humidity Effects . . . 59
3.8.1 RH Effects on Viruses . . . 60
3.8.2 RH Effects on Bacteria . . . 62
3.8.3 RH Effects on Bacterial and Fungal Spores . . . 67
3.9 Modeling Photoreactivation . . . 68
3.10 Air Temperature Effects . . . 70
References . . . 70

4 UV Rate Constants . . . 73
4.1 Introduction . . . 73
4.2 Rate Constants and Survival Curves . . . 74
4.3 UV Rate Constant Database . . . 74
4.3.1 Bacteria Rate Constants . . . 75
4.3.2 Virus Rate Constants . . . 76
4.3.3 Fungi Rate Constants . . . 81
4.4 Surface UV Rate Constants . . . 82
4.5 Water Rate Constants . . . 84
4.6 Airborne Rate Constants . . . 86
4.7 Narrow Band UVC vs. Broadband UVB/UVC . . . 87
4.8 Relative Humidity Effects . . . 88
4.9 Rate Constant Determinants . . . 90
4.10 UV Scattering in Water . . . 94
4.11 Prediction of UV Susceptibility . . . 96
References . . . 105

5 UVGI Lamps and Fixtures . . . 119
5.1 Introduction . . . 119
5.2 Types and Characteristics of UV Lamps . . . 120
5.3 Lamp Power, Size, and Nomenclature . . . 123
5.4 Lamp Ballasts . . . 125
5.4.1 Magnetic Ballasts . . . 125
5.4.2 Electronic Ballasts . . . 126
5.5 Microwave UV Lamps . . . 126
5.6 UV LEDs . . . 127
5.7 Pulsed UV Lamps . . . 129
5.8 Lamp Ratings . . . 129
5.9 Lamp Shapes . . . 129
5.10 Lamp Fixtures . . . 130
5.11 Upper Room Lamp Fixtures . . . 131
5.12 Lamp Cooling Effects . . . 132

5.13 Ozone Generation . . . 135
5.14 Lamp Maintenance . . . 135
References . . . 136

6 Systems and Equipment . . . 139
6.1 Introduction . . . 139
6.2 Air Disinfection Systems . . . 139
6.2.1 In-Duct Air Disinfection . . . 140
6.2.2 Recirculation Units . . . 142
6.2.3 Upper Room Systems . . . 143
6.2.4 UV Barrier Systems . . . 144
6.2.5 Overhead Tank Disinfection . . . 145
6.3 Surface Disinfection Systems . . . 145
6.3.1 Equipment and Packaging Disinfection . . . 146
6.3.2 Cooling Coil Disinfection . . . 147
6.3.3 Lower Room Disinfection . . . 148
6.3.4 Overhead Surgical Site Disinfection . . . 149
6.3.5 Area/Room Disinfection . . . 150
6.3.6 Food Surface Disinfection . . . 151
6.3.7 Mold Remediation Systems . . . 152
6.3.8 UV Hand Wands . . . 152
6.4 UV Reflective Materials . . . 153
6.5 UV Light Baffles . . . 153
6.6 UV-Transmittant Materials . . . 155
6.7 UV Absorbers . . . 155
6.8 Flow Straighteners . . . 156
6.9 PCO Systems . . . 156
6.10 Controls and Integral Sensors . . . 157
References . . . 157

7 UVGI System Modeling . . . 159
7.1 Introduction . . . 159
7.2 UV Lamp Modeling . . . 160
7.3 UV Reflectivity Modeling . . . 163
7.3.1 Modeling Specular Enclosures . . . 163
7.3.2 Modeling Diffuse Enclosures . . . 166
7.3.3 Combined Specular and Diffusive Reflectivity . . . 170
7.4 Air Mixing Effects . . . 171
7.5 UV System Optimization . . . 173
References . . . 175

8 Airstream Disinfection . . . 177
8.1 Introduction . . . 177
8.2 UV Air Disinfection Performance . . . 177
8.3 Filtration Performance . . . 185

8.4 Combined Performance of Filtration and UVGI 186
8.5 In-duct Air Disinfection Systems 190
8.6 EPA Test Results 191
8.7 Unitary UV Systems 195
8.8 Barrier Systems 197
8.9 Zonal Modeling 198
8.9.1 Steady State Single Zone Model 198
8.9.2 Transient Modeling 200
8.9.3 Multizone Modeling 203
8.10 Zonal Protection Factors 203
8.11 UV Air Disinfection Field Trials 206
References 207

9 Upper Room UV Systems 211
9.1 Introduction 211
9.2 Types and Design of Fixtures 212
9.3 Upper Room System Sizing 216
9.4 Air Mixing Effects 220
9.5 Room Design 223
9.6 Performance 224
9.7 Testing 227
9.8 Upper Room UV Safety 229
References 230

10 UV Surface Disinfection 233
10.1 Introduction 233
10.2 Microbial Growth Control 233
10.3 Modeling Surface Disinfection 234
10.4 UV Cabinets 236
10.5 Area Disinfection Systems 238
10.6 Cooling Coil Irradiation 239
10.7 Overhead Surgical Site Systems 246
10.8 Lower Room Systems 249
10.9 Food and Packaging Irradiation 250
10.10 Summary 252
References 252

11 UVGI Guidelines and Standards 255
11.1 Introduction 255
11.2 UVGI Electrical Guidelines 256
11.3 Testing Guidelines and Standards 258
11.4 UVGI Application Guidelines 262
11.5 UVGI Safety Guidelines 277
References 283

12 UVGI Safety 287
12.1 Introduction 287
12.2 The Germicidal UV Spectrum 287
12.3 Biological Effects of UV Exposure 288
12.3.1 UV Effects on Eyes 289
12.3.2 UV Effects on Skin 291
12.4 UV Exposure Limits 293
12.5 UV Measurement 299
12.6 UV Protection and Control Measures 300
12.6.1 In-duct UVGI System Safety 300
12.6.2 Unitary UVGI System Safety 301
12.6.3 Upper Room UVGI Safety 301
12.6.4 Lower Room UVGI Safety 302
12.6.5 Cooling Coil UVGI Safety 303
12.6.6 Equipment Disinfection UVGI Safety 303
12.6.7 Overhead Surgical Site System Safety 304
12.6.8 Area Decontamination UVGI Safety 304
12.7 Personal Protective Equipment (PPE) 305
12.8 Labeling 306
12.9 Ozone Generation Hazards 307
12.10 Lamp Breakage and Mercury Risks 308
References 309

13 Ultraviolet Radiometry 313
13.1 Introduction 313
13.2 Lamp Electrical Characteristics 313
13.3 UV Irradiance and UV Dose 314
13.4 Measurement Equipment 315
13.5 UV Lamp Ratings 318
13.6 Lamp Irradiance Measurements 319
13.7 Lamp Cooling and Heating Effects 323
13.8 UV Reflectivity 323
13.9 UV Transmittance 325
13.10 UV Absorptance 325
13.11 Reflective Lamp Fixtures and Enclosures 326
13.12 UV Dose Measurement 327
13.13 Spherical Actinometry 328
13.14 Testing Applications 328
13.14.1 Laboratory Testing of Equipment 329
13.14.2 In-duct UVGI System Testing 329
13.14.3 Cooling Coil Systems 330
13.14.4 Overhead Surgical Site Systems 331
13.14.5 Upper Room Systems 332
13.14.6 Lower Room Systems 333

13.14.7 Area Disinfection Systems 333
References 334

14 Microbiological Testing 337
14.1 Introduction 337
14.2 Microbiological Testing 337
14.3 Biodosimetry 338
14.4 Test Microbes 338
14.5 Test Materials and Equipment 340
14.6 Surface Sampling 341
14.7 Air Sampling 346
14.8 Sampling Applications 348
14.8.1 UV Rate Constants 348
14.8.2 Cooling Coil Disinfection Systems 351
14.8.3 In-duct Air Disinfection Systems 352
14.8.4 Upper Room Systems 353
14.8.5 Lower Room Systems 353
14.8.6 Overhead Surgical Site Systems 354
14.8.7 Area Disinfection Systems 355
14.9 Evaluating Sampling Results 355
14.10 Virus Sampling 357
References 357

15 UV Effects on Materials 361
15.1 Introduction 361
15.2 UV Effects on Materials 361
15.3 Activation Spectra 365
15.4 Solarization of Glass 366
15.5 Photodiscoloration 367
15.6 Photodegradation 368
15.7 Damage to Houseplants 372
15.8 Ozone Production 372
15.9 Protective Coatings 373
15.10 UV Absorbers 375
15.11 Photodegradation Testing 377
References 378

16 Pulsed UV Systems 383
16.1 Introduction 383
16.2 Pulsed UV Disinfection 384
16.3 The PUV Spectrum and Germicidal Effectiveness 385
16.4 Modeling PUV Dose 387
16.5 Modeling PUV Decay Curves 389
16.6 A General Model for PUV Disinfection 394
16.7 Pulsed Light Disintegration 395
References 397

17 Health Care Facilities 399
17.1 Introduction 399
17.2 Nosocomial Infections 400
17.3 Operating Rooms and ICUs 401
17.4 Isolation Rooms 406
17.5 General Areas 408
17.6 Hallways and Storage Areas 410
17.7 Dental Offices 412
17.8 AIDS Clinics 413
17.9 Hospital Laboratories 414
17.10 Animal Laboratories and Veterinary Facilities 414
References 418

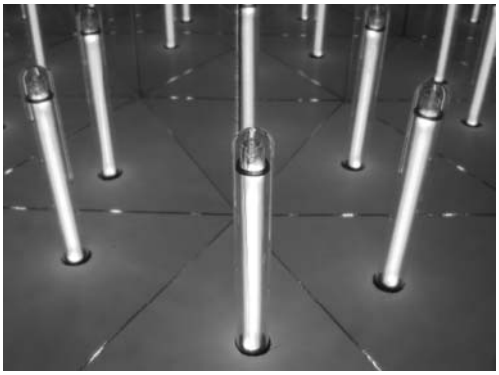
18 Commercial Buildings 423
18.1 Introduction 423
18.2 Office Buildings 423
18.3 Industrial Facilities 425
18.4 Food Industries 427
18.5 Educational Facilities 431
18.6 Museums and Libraries 432
18.7 Agricultural and Animal Facilities 437
18.8 Malls, Airports, and Places of Assembly 441
18.9 Aircraft and Transportation 442
18.10 Sewage and Waste Facilities 443
References 444

19 Residential Applications 449
19.1 Introduction 449
19.2 Residential Homes 449
19.3 Apartments 452
19.4 Hotels and Dormitories 453
References 454

20 Bioterrorism Defense 457
20.1 Introduction 457
20.2 Bioweapons 457
20.3 Biodefense of Buildings 461
20.4 UV Systems for Biodefense 464
20.5 UV Bioremediation 467
References 468

Appendices 471

Index 493



Chapter 1

Introduction

1.1 Ultraviolet Germicidal Irradiation (UVGI)

Ultraviolet germicidal irradiation (UVGI) is defined as the use of ultraviolet (UV) wavelengths of light in the germicidal range (200–320 nm) for the disinfection of air and surfaces. The term 'UVGI' was originally coined by the International Commission on Illumination (CIE) and adopted later by the Centers for Disease Control (CDC), and this term distinguishes disinfection applications from the non-germicidal UVA wavelengths of black lights and suntan lamps (320–400 nm). UVGI is also used to distinguish air and surface disinfection applications from those in water (CIE 2003). Throughout this book the terms 'UVGI' and 'UV' will be used interchangeably, with the understanding that in every context, unless otherwise noted, both terms refer to the germicidal wavelengths of UVC (200–280 nm) and UVB (280–320 nm). UV radiation below 320 nm is actinic, which means it causes photochemical reactions. UVA radiation (320–400 nm) is not considered germicidal and is not specifically addressed in this book (except in relation to pulsed light). Table 1.1 summarizes the definitions of the primary bands of UV radiation. Previously, UVA was considered to extend down to 315 nm, but the range 315–320 nm was found to have some minor germicidal effects. The UVA band, and therefore the UVB band also, have been redefined by various organizations such that all actinic UV radiation is now contained strictly within the UVB and UVC range. This division allows UVA to be completely non-germicidal and conveniently places all the germicidal UV into the UVB and UVC bands.

The definitions of the UV bands UVA, UVB, and UVC given in Table 1.1 have not yet been fully incorporated into every relevant guideline or adopted by every agency, but are likely to be adopted eventually and universally. VUV (Vacuum Ultraviolet) does not transmit through air since it is rapidly absorbed and therefore the VUV band is of no interest in air and surface disinfection, and is not addressed further in this book.

This introductory chapter presents some other basic definitions and subjects which provide a background for the subsequent chapters, where these concepts

W. Kowalski, *Ultraviolet Germicidal Irradiation Handbook*,
DOI 10.1007/978-3-642-01999-9_1, © Springer-Verlag Berlin Heidelberg 2009

Table 1.1 Primary bands of ultraviolet radiation

Band	Wavelength, nm	Type and classification		
UVA	320–400	Non-germicidal (Near-UV, Blacklight)		
UVB	280–320	Erythemal	**Germicidal**	**Actinic**
UVC	200–280	Ozone-producing		
VUV	100–200	Vacuum ultraviolet		

will be addressed in greater detail. The chapters in this book are arranged to first address the background information, including theory and mathematical modeling, then equipment and design methods, and finally testing and applications. In the Appendices are provided tabulations of data and information that are useful and that will be referenced throughout this book.

1.2 Brief History of Ultraviolet Disinfection

The story of ultraviolet light begins with Isaac Newton and his contemporaries. In 1672, Isaac Newton published a series of experiments with prisms that resolved sunlight into its constituents colors, red through violet. The effects of sunlight on man, microorganisms, and chemicals became a matter of great interest and experimentation in the 1800s. In 1814, Fraunhofer mapped over 500 bands of sunlight, some of which were in the ultraviolet region. In 1842, Becquerel and Draper each independently showed that wavelengths between 340 and 400 nm induced photochemical changes on daguerreotype plates (Hockberger 2002).

UV Lamp development predates sunlight studies on bacteria. In 1835, Wheatstone invented the first mercury (Hg) vapor arc lamp, but it was unstable and short-lived. Fizeau and Foucault (1843) reported problems with their eyes after experimenting with a carbon arc lamp, and speculated that it was due to 'chemical rays.' In 1850, Stokes used aluminum electrodes to produce a 'closed' arc lamp in a quartz tube that emitted UV rays to 185 nm (Hockberger 2002).

The earliest scientific observations of the germicidal effects of ultraviolet radiation began with Downes and Blunt (1877) who reported that bacteria were inactivated by sunlight, and found that the violet-blue spectrum was the most effective. In 1885, Arloing and Duclaux demonstrated that sunlight had a killing effect on *Bacillus anthacis* and *Tyrothrix scaber*, respectively. Widmark (1889, 1889a) published studies confirming that UV rays from arc lamps were responsible for skin burns, using a prism to separate the UV spectrum and water to block the infrared rays. It was demonstrated in 1892 that ultraviolet light was responsible for this action with tests on *Bacillus anthracis* (Ward 1892). Also in 1892, Geisler used a prism and a heliostat to show that sunlight and electric arc lamps were lethal to *Bacillus typhosus*. Finsen (1900) performed the first rigorous analysis of the effects of UV light. The UV spectrum around 250 was identified as biocidal by Barnard and Morgan (1903), and the range was narrowed by Newcomer (1917), and isolated to

253.7 nm by Ehrismann and Noethling (1932). Table 1.2 summarizes most of the critical developments in the history of UV research and applications.

The first use of UV to disinfect drinking water is said to have been in 1906 according to von Recklinghausen (1914). In 1909/1910 the first water disinfection

Table 1.2 Chronology of critical events in UV history

Year	Event	Reference
1814	Fraunhofer maps spectral bands of sunlight	Hockberger (2002)
1835	Wheatstone invents first mercury vapor arc lamp	Hockberger (2002)
1850	Stokes invents quartz arc lamp that produces to 185 nm	Hockberger (2002)
1842	Becquerel and Draper find 340–400 nm light photoreactive	Hockberger (2002)
1877	Bactericidal effects of sunlight first demonstrated	Downes and Blunt (1877)
1889	UV light demonstrated to be erythemal	Widmark (1889)
1892	UV component of sunlight identified as biocidal	Ward (1892)
1892	Geissler demostrates lethality of arc lamps to *B. typhosus*	Hockberger (2002)
1903	UV spectrum from 226 to 328 nm found to be germicidal	Barnard and Morgan (1903)
1904	First quartz lamp for UV developed	Lorch (1987)
1906	UV first used to disinfect drinking water	von Recklinghausen (1914)
1909	First European applications for UV water disinfection	AWWA (1971)
1912	Henri found shorter UV wavelengths don't penetrate	Henri (1912)
1916	First USA applications of UV for water disinfection	AWWA (1971)
1921	UV photoreactivity with TiO_2 first demonstrated	Renz (1921)
1925	UV photodegradation of materials first demonstrated	Luckiesh and Taylor (1925)
1927	First erythemal action spectrum published	Hausser and Vahle (1927)
1927	Bactericidal action of UV first quantified scientifically	Bedford 1927, Gates (1929)
1928	Virucidal action of UV first quantified scientifically	Rivers and Gates (1928)
1929	Fungicidal action of UV first quantified scientifically	Fulton and Coblentz (1929)
1932	UV germicidal peak at 253.7 nm isolated	Ehrismann and Noethling (1932)
1932	Erythemal spectrum of UV first quantified	Coblentz et al. (1932)
1936	First overhead UV system in hospitals	Wells and Wells (1936), Hart (1936)
1936	UV photoreactivation phenomena first identified	Prat (1936)

Table 1.2 (continued)

Year	Event	Reference
1937	First upper air application in schools	Wells (1938)
1938	First fluorescent gas discharge UV lamp	Whitby and Scheible (2004)
1940	UV first applied to air conditioning systems	Rentschler and Nagy (1940)
1942	First UV air disinfection sizing guidelines	Luckiesh and Holladay (1942)
1942	Upper and lower UV applied to Army/Navy barracks	Wells et al. (1942)
1950	First catalog sizing methods	Buttolph and Haynes (1950)
1954	First air conditioner application	Harstad et al. (1954)
1954	Faulty British study concludes UV is ineffective	MRC (1954)
1957	Riley proves effectiveness of UV for TB control	Riley et al. (1957)
1974	First microbial growth control systems	Grun and Pitz (1974)
1985	Cooling coil UV systems in use in European breweries	Philips (1985)
1994	CDC acknowledges UV effectiveness for TB control	CDC (2005)
1996	First cooling coil irradiation system in US	Scheir (2000)
1997	First UV light emitting diodes (LEDs) at 265 nm	Guha and Bojarczuk (1998)
1999	WHO recommends UVGI for TB control	WHO (1999)
2000	US army recommends UVGI for disease isolation	USACE (2000)
2003	CDC formally sanctions UVGI use in hospitals	CDC (2003)
2003	FEMA sanctions UVGI as a biodefense option for buildings	FEMA (2003)
2003	First in-duct UVGI system demonstrated to reduce illness symptoms and airborne contamination	Menzies et al. (2003)
2003	ASHRAE forms UV air and surface treatment committee	Martin et al. (2008)
2005	Federal government specifies UV for cooling coil disinfection	GSA (2003)
2007	Overhead UV system proven to reduce SSIs in ORs	Ritter et al. (2007)

system was operated at Marseilles, France. The first evidence that UV light produced photochemical effects on microorganisms was presented by Henri (1914). In 1916 the first US system for water disinfection was tested at Henderson, KY (AWWA 1971). In 1921, Renz demonstrated that UV could cause photoreactions with titanium oxide (TiO2). Hausser and Vahle (1927) produced the first detailed action spectrum for erythema. Bedford (1927) and Gates (1929) were among the first to establish UV dosages necessary for bacterial disinfection. Fungal disinfection dosages were first published by Fulton and Coblentz (1929). The first studies on UV irradiation of viruses appear to have been those published by

Rivers and Gates (1928) and Sturm et al. (1932). Coblentz et al. (1932) refined the erythemal action spectrum.

The 1930s saw the first applications of UV systems in hospitals to control infections (Wells and Wells 1936, Hart and Sanger 1939, Robertson et al. 1939, Kraissl et al. 1940, Overholt and Betts 1940). The first Upper Room UV systems appear to be those installed by Wells (1938). In the 1940s the first detailed design and analysis of UV air disinfection were published along with basic guidelines for applying UV in ventilation systems (Rentschler and Nagy 1940, Sharp 1940, Wells 1940, Buchbinder and Phelps 1941, DelMundo and McKhann 1941, Luckiesh and Holladay 1942, Sommer and Stokes 1942, Henle et al. 1942, Hollaender 1943). The first attempts to use UV systems to control respiratory infections in schools and barracks occurred shortly thereafter (Wells et al. 1942, Wells 1943, Schneiter et al. 1944, Wheeler et al. 1945, Perkins et al. 1947, Higgons and Hyde 1947). Several early attempts were made to develop rigorous sizing methods and engineering guidelines for UV applications (Luckiesh and Holladay 1942a, Luckiesh 1945, 1946).

By the 1950 s it had been well-established that UV irradiation was effective at disinfecting both air and surfaces, and new engineering applications were being developed. General Electric catalogs detailed a wide variety of UV applications including various methods of installing UV lamps inside ducts and air conditioners (Buttolph and Haynes 1950, GE 1950). Harstad et al. (1954) demonstrated that installation of UV lamps in air conditioners would reduce airborne contamination, and that microorganisms were impinging upon and collecting on internal AHU surfaces. Bacterial growth on cooling coils had been recognized as a potential health problem as early as 1958 (Walter 1969). The first evidence that air cooling equipment could actually cause respiratory infections was presented by Anderson (1959) when an air cooling apparatus was found to be contaminated with microbial growth. This very same concern had been raised in hospital environments since about 1944 but the possibility of growth of bacteria on air-conditioning cooling coils wasn't conclusively demonstrated until 1964 (Cole et al. 1964). The growth of microbes on other equipment like filters and dust inside air-conditioning ducts was first demonstrated by Whyte (1968). The dissemination of microbes by ventilation systems and their potential to cause respiratory infections became widely recognized in the late 1960 s in both the medical and engineering professions (Banaszak et al. 1970, Schicht 1972, Zeterberg 1973). It was understood at this time that microbial growth could occur anywhere that air came into contact with moisture (Gunderman 1980, Ager and Tickner 1983, Spendlove and Fannin 1983). The first UVGI system designed specifically for disinfecting the surfaces of air handling equipment, including humidifier water and filters, was detailed by Grun and Pitz (1974). Luciano (1977) detailed many applications of UVGI, including hospital applications in which the UV lamps are specifically placed upstream of the cooling coils and downstream of the filters. In 1985 Phillips published a design guide in which the first definitive description of applications of UV lamps for the control of microbial growth were presented (Philips 1985). The Philips design guide mentions European installations that were already in operation prior to 1985. In January of 1996 the first UVGI system in the US designed for controlling

microbial growth on cooling coils was installed by Public Service of Omaha (PSO) in Tulsa (Scheir 2000). In the same year, the Central and Southwest Corporation followed the PSO example and began realizing considerable energy savings (ELP 2000).

Although UVGI systems had been in use in hospitals since 1936 but it wasn't until 2003, some sixty years later, that the CDC formally acknowledged that UV systems were effective and could be used in hospitals with one caveat – UV Upper Room and in-duct systems could only be used to supplement other air cleaning systems (CDC 2003). In 1957, Riley and associates successfully completed a demonstration of how UV air disinfection could control the spread of tuberculosis (TB) in hospital wards (Riley et al. 1957). It wasn't until 1994, over forty years later, that the Centers for Disease Control (CDC) acknowledged that UV could be effective for controlling TB, in response to the growing worldwide TB epidemic which had resisted control by traditional methods (CDC 2005). In 2003, The influential American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) formed a task group to focus on UV air and surface treatment (TG2.UVAS) which became the standing Technical Committee TC 2.9 in 2007 (Martin et al. 2008).

1.3 Units and Terminology

A variety of units have been used in UV disinfection for the irradiance and the UV dose. The irradiance, sometimes called intensity, has the preferred units of W/m^2 in air and surface disinfection. The UV dose (aka fluence rate) has the preferred units of J/m^2 in air and surface disinfection. Conversion factors for the various units that have been used in the literature are provided in Table 1.3. The use of Table 1.3 is straightforward as shown in the following examples. Note that a joule (J) is equivalent to a watt-second (W-s), and that a W/m^2 is equal to a $\mu W/mm^2$.

Example 1: Convert the irradiance 144 mW/cm^2 (milliwatts per square centimeter) to units of W/m^2 (watts per square meter)

Answer: Read downwards from the first column, mw/cm^2 to the gray box and then over to the second column, W/m^2, where the conversion factor is seen to be 10. Multiply $144 \times 10 = 1440\ W/m^2$.

Example 2: Convert the UV dose 33 $\mu J/cm^2$ (microJoules per square centimeter) to units of J/m^2 (Joules per square meter).

Answer: Read up from the fourth column, $\mu J/cm^2$, to the gray box, and then over to the second column, J/m^2, where the conversion factor is seen to be 0.01. Multiply $33 \times 0.01 = 0.33\ J/m^2$.

The term 'UVC' is often used today to encompass all applications of germicidal UV but the correct definition of this term is, of course, the band of UV wavelengths between 200 and 280 nm, and this strict definition is the one used throughout this book. For example, a UV lamp could refer to any lamp that produces any UV wavelengths, including black light and suntan lamps (although in this book only

Table 1.3 Units of Irradiance and UV Dose

Conversion factors for irradiance (Read down from units to gray block and then horizontally for unit equivalence.)					
mW/cm^2	W/m^2 $\mu W/mm^2$ J/m^2–s	erg/mm^2–s	$\mu W/cm^2$	erg/cm^2–s	W/ft^2
1	10	100	1000	10000	1.07639
0.1	1	10	100	1000	0.107639
0.01	0.1	1	10	100	0.010764
0.001	0.01	0.1	1	10	0.001076
0.0001	0.001	0.01	0.1	1	0.000108
0.929	9.29	92.90	929.0	9290	1
mJ/cm^2	μW–s/mm^2 W–s/m^2	erg/mm^2	$\mu J/cm^2$	erg/cm^2	W–s/ft^2
mW–s/cm^2	J/m^2		μW–s/cm^2		
Conversion factors for UV Dose (Exposure time = 1 second) (Read up from units to gray block and then horizontally for unit equivalence.)					

germicidal UV lamps are addressed). The term 'UVGI lamp' specifically refers to lamps that produce UV wavelengths in the actinic 'broad-band' range between 200 and 320 nm (excluding black lights and sunlamps). The term 'UVC lamp' specifically refers to lamps that produce UVC wavelengths in the 'narrow-band' range 200–280 nm. In current and common usage, the term 'UVC' often implies that the UVC band is the only contributor to the germicidal effect, but this implication is often incorrect and such usage is avoided in this text – wherever the term 'UVC' is used herein it refers specifically to the UVC band of radiation. Other terms such as UVR (ultraviolet radiation) and GUV (germicidal ultraviolet) have also been used in a germicidal context in the past.

The term 'germicidal' implies that these UV systems destroy, kill, or inactivate microorganisms such as viruses, bacteria, and fungi. Technically, viruses are molecules, and so it customary to refer to viruses as being inactivated rather than killed. In all cases, germicidal action means disinfection, and disinfection implies a reduction in the microbial population, whether in air, water, or on surfaces. Microbial populations are measured in terms of cfu, or colony-forming units (i.e. grown on petri dishes). In the case of viruses, the appropriate measure of viral populations is pfu, or plaque-forming units. However, wherever the term 'cfu' is used in this book, it will be considered to apply to both viruses and bacteria (as a matter of convenience), with the reader's understanding that the correct terminology for viruses is pfu, whether it is used or not. The density of microbes in air is always given in units of cfu/m^3 (although some older texts use cfu/ft^3). The density of microbes on surfaces is given in cfu/cm^2 (in older texts it is cfu/in^2). The disinfection of air will therefore be measured in terms of a reduction in the airborne density in cfu/m^3, and the disinfection of surfaces is measured in terms of the reduction of cfu/cm^2.

Sterilization is a related term that implies the complete elimination of a microbial population. It is difficult, however, to actually demonstrate the complete elimination of a microbial population since any microbiological test will have some limit of

accuracy. As a practical convenience in air disinfection applications, and for analytical purposes, 'mathematical sterilization' can be assumed to represent a disinfection rate of six logs or better, when there are no survivors. This definition may not apply to water UV disinfection, but in air disinfection applications it would be most unusual to have airborne densities on the order of a million cfu/m^3, and typical airborne densities are in the range of a few thousand cfu/m^3. Obviously, with densities of a few thousand cfu/m^3, a three or four log reduction (1000–10,000 cfu/m^3) would result in sterilization, and a six log reduction is an adequate definition of sterilization for air disinfection applications. Surface disinfection is another matter altogether and the densities of surface contamination are neither well understood nor well defined, and so the 'mathematical definition' of sterilization for surface disinfection is left undefined in this text.

1.4 Air vs. Water Disinfection

The design of UV systems for water disinfection differs from that of air and surface disinfection applications and therefore the cumulative knowledge accrued in the water industry is of limited direct use for air and surface disinfection applications. UV rays are attenuated in water and this process has no parallel in air disinfection, even with saturated air. The attenuation of UV irradiance in water occurs within about 15 cm and this necessitates both higher UV power levels and closely packed arrays of UV lamps. The estimates of UV doses required for water disinfection are on the order of ten times higher than those needed in air disinfection applications, and this difference distorts any attempt to use water UV system sizing methods to design air disinfection systems. Furthermore, the array of particular microorganisms of concern in the water industry differs considerably from those found in air and therefore water-based UV rate constants are of use only where the microbial agent is both airborne and waterborne (i.e. *Legionella*), or is also surface-borne, and for theoretical analysis. Some overlap in waterside and airside UV applications also exists in the area of foodborne pathogens, where certain foodborne pathogens may become airborne, and where they may exist as surface contamination amenable to UV disinfection.

Although the UV exposure dose in air is a simple function of airflow and exposure time, and the UV irradiance field in air is not too difficult to define, the susceptibility of airborne microbes is a complex function of relative humidity and species-dependent response. It has often been thought that the UV susceptibility of microbes in air at 100% relative humidity (RH) should correspond to their susceptibility in water, but this proves to be overly simplistic and it can only be said that UV susceptibility at high RH approaches that in water. As a result of these various differences between water-based UV disinfection and UVGI air and surface disinfection, research into the former provides limited benefits to research into air-based disinfection, and the subject of water disinfection is not addressed in this book except insofar as it has some specific impact on air and surface disinfection and in the matter of their common theoretical aspects. The UV rate constant

database in the Appendices, addresses all known UV studies on microbial disinfection, including those for waterborne and foodborne pathogens and allergens. There are a wide variety of detailed texts on the subject of water disinfection with UV (many times more than for airside UV disinfection) and readers who wish to familiarize themselves with waterside UV technology and methods should consult these texts directly (see for example, Bolton and Cotton 2008). However, the information provided herein on UVGI theory and UV inactivation rate constants may be of no little interest to those involved in water disinfection.

1.5 Surface Disinfection

Surface disinfection refers to either the disinfection of building and ventilation system internal surfaces, or the disinfection of equipment and material surfaces, such as dental and medical equipment. Like water systems, surface UV disinfection systems have a long history of success. The design and operation of surface UV systems, however, have much more in common with air disinfection than do water systems. Contaminated surfaces are often a source of airborne microbes, and airborne microbes often produce surface contamination. The interaction of air and surface contamination processes makes the issue of air vs. surface disinfection almost inseparable for some applications, such as in the health care industry and the food industry. The disinfection of cooling coil surfaces, for example, removes mold spores from the coils and prevents subsequent aerosolization, thereby helping keep the air clean. UV systems for coil disinfection applications also disinfect the air directly and so such systems often perform simultaneous air and surface disinfection functions.

One of the main differences between air and surface disinfection with UV is that the relevant UV rate constants differ under these two types of exposure – airborne rate constants tend to be higher in air, under normal humidity. That is, microbes are more vulnerable in air, whereas microbes on surfaces appear to have a certain degree of inherent protection. Although the matter remains to be resolved by future research, the available database for UV rate constants for microbes on surfaces is useful as a conservative estimate of airborne rate constants, as are water-based rate constants, whenever airborne rate constant studies do not exist.

Since airborne microbes are often surface-borne, and vice-versa, and for the various reasons mentioned above, the overlap between these topics, air and surface UV disinfection, is extensive. In fact, the subject of surface disinfection has considerably more in common with air disinfection than water disinfection and often the two technologies are inter-related. It is appropriate, therefore to treat air and surface UV disinfection together, as in this text, and it should be understood that most air disinfection systems will simultaneously perform some surface disinfection function, intentionally or otherwise. Similarly, many UV surface disinfection systems (i.e. Lower Room systems, Overhead Surgical systems) will also perform some air disinfection functions, by design or otherwise.

1.6 Air Disinfection

Airborne pathogens and allergens present a much greater threat to human health than water-based microbes, in terms of total incidence and net costs of health care, but there are far fewer air disinfection systems in place than water disinfection systems, and much less information is available for airborne UV disinfection than for water applications. The success of UVGI for air disinfection application has also been subject to much interpretation and even outright dismissal, in spite of repeated demonstrations of its effectiveness. After decades of research, the field of airborne UV disinfection remains fraught with unknowns and misconceptions, and applications are far less numerous than they perhaps should be. The subsequent chapters attempt to consolidate the entire knowledge base relevant to UVGI and to demonstrate how the careful application of proper design principles and new approaches can produce results as predictable and reliable as those of water disinfection systems. New computational methods, combined with a wealth of recent design and installation experience and ongoing research, now allows systems to be installed with fairly high levels of confidence in terms of their performance.

Methods for demonstrating in-place performance, along with various guidelines and standards for such installations, have brought the field of UVGI from an uncertain art to a nearly complete science. The key missing component at this time is conclusive evidence that UVGI air disinfection reduces the incidence of airborne disease, a matter that will require years of data collection, once there are sufficient and adequate installations available for monitoring. Some current studies are exploring this avenue of research and preliminary results suggest that UVGI is, as theory and analysis predicts, effective in reducing both the symptoms and incidence of various airborne diseases. As applications increase, this database should eventually provide reliable evidence that may lead to full economic justification of UVGI installations in health care facilities, schools, and other types of buildings. The widespread use of UV for air disinfection in buildings is likely an eventuality that will pay economic and health dividends to future generations.

1.7 Air Disinfection Field Studies

The use of UV to disinfect air goes back some eighty years, and yet applications are still far from being common in modern buildings. Although nine out of ten UVGI field studies had positive results, the few that did not meet grand expectations were cited most often as proof of failure. In 1936 Hart used an array of UV lamps to sterilize supply air in a surgical operating room (Hart 1937). In 1937 the first installation of UV lamps in a school ventilation system dramatically reduced the incidence of measles, and subsequent applications enjoyed similar successes (Riley 1972). In the late 1940s, Wells and his associates installed UV systems across entire communities and demonstrated reductions in community disease transmission rates (Wells and Holla 1950). In the late 1950 s experiments using guinea pigs demonstrated the elimination of tuberculosis (TB) bacilli from hospital ward exhaust air

(Riley and O'Grady 1961). A plethora of designs that were more imitative then engineered followed these early applications. The result was a mixture of successes and failures. In one poorly planned study by the MRC, investigators failed to achieve statistically significant reductions of disease and concluded erroneously that UV failed to reduce disease incidence (MRC 1954). The MRC study put a severe damper on further development of UV technology in the 1950 s and 1960 s, and as a result of this study being widely quoted (and in spite of it being widely criticized by experts), brought a near halt to further implementations and slowed research (Riley 1980, 1980a). This setback of the UV industry cannot be measured in terms of lost development, lost field data, lost health care costs, or lost lives, but there are those who today continue to insist that UVGI is an unproven 'snake oil' technology. We must convince them otherwise.

As a result of an apparently imperfect record of success, UVGI was widely ignored in various guidelines and standards, particularly in health care settings, where it should have been directly addressed. Without the sanction of the highest health authorities, UVGI languished and was largely ignored in health care settings where it would have done the most good. This checkered history is reflected in various guidelines that decline to mention the use of UVGI. Only a select few of the most well-informed hospitals and researchers took the time to investigate and adopt UV technologies, often with great success (Goldner and Allen 1973, Goldner et al. 1980, Nardell 1988). Recently, new research has reaffirmed what the original studies had always said, that UV technology can have a major impact on the reduction of various types of nosocomial and community-acquired infections (Menzies et al. 2003, Ritter et al. 2007, Escombe et al. 2009).

1.8 Pathogens and Allergens

Pathogens are any microbes that cause infections in humans and animals, and these include viruses, bacteria, and fungi. Some larger microbes, like protozoa, may also cause infections but these parasites are generally too large to be airborne. Therefore, this book primarily addresses only viruses, bacteria, and fungi, including bacterial spores and fungal spores, as air and surface contaminants. Insects, like dust mites, are not eradicable by UV and are not addressed in this text. All of the viruses listed in Appendix B are pathogens or bacteriophages, as are most of the bacteria in Appendix A and some of the fungi in Appendix C.

Allergens are microbes, biological products, and compounds that induce allergic reactions in atopic, or susceptible, individuals. Compounds and biological products (i.e. VOCs and pet dander) are generally not very susceptible to UV destruction (although they are easily removed by filters) and so they are not specifically addressed in this book. The allergens addressed in this book are strictly fungi and bacteria – there are no viral allergens. Some pathogens may also be allergens. Almost all of the fungi listed in Appendix C are allergens, and many of these are also pathogens. Almost all of the bacteria listed in Appendix A are pathogens, and some of these are also allergens.

Some bacteria, and virtually all fungi, can form spores. In the normal or growth state (called 'vegetative') bacteria exist as cells, and fungi exist as cells or yeast. Spore-forming (sporulating) bacteria and fungi will form spores under the right conditions (usually adverse conditions). Spores are dormant forms, usually more compact than the cell forms, round or ovoid shaped, and can resist heat, dehydration, and cold much better than the cell (or vegetative) form. They also tend to be resistant to UV exposure. Since they are typically smaller than the original cells, spores tend to become airborne easily and can be transported outdoors. Spores require only warmth, moisture, and shade to germinate, or return to a vegetative state, and require only nutrients to grow and multiply.

Some bacteria and fungi produce toxins, including endotoxins and exotoxins. UV has a limited effect on toxins but prolonged exposure can reduce toxin concentrations (Anderson et al. 2003, Asthana and Tuveson 1992, Shantha and Sreenivasa 1977). High levels of growth are required, usually under adverse conditions, for microbes to produce toxins, and since UV destroys toxin-producing bacteria and fungi, it is unlikely that sufficient levels of toxins will remain after UV disinfection to pose toxic hazards.

1.9 Current Research

In spite of the extensive research results available on UVGI air and surface disinfection, much work remains to be done. Recent studies have demonstrated the effectiveness of UVGI and have hinted at the possible reduction of airborne disease in commercial office buildings. The ability of UVGI to save costs in cooling coil maintenance has been fairly well established. There is also a need for more research to determine UV rate constants for a wider array of pathogens. Towards this end has been provided a guideline for laboratory testing (included in this book) that should facilitate the production of reproducible test results, something that has not always been the case in the past.

In addition to providing the most up-to-date information from current literature of UVGI, this text also provides the fruits of the author's research into UV susceptibility, including a model for relative humidity effects in air, and a genomic model for predicting the UV susceptibility for viruses (addressed in Chaps. 2 and 4). Also presented here for the first time is the author's research on pulsed UV light modeling.

Perhaps the most important applications of UVGI today is in the health care industry, which is in dire need of solutions to the problem of hospital-acquired (nosocomial) infections. Such infections have now spread outwards to become community-acquired infections and it is likely this pattern will keep repeating with new and emerging pathogens and drug-resistant strains until a more effective solution is implemented on a wide scale. UVGI can play a major role in limiting the spread of nosocomial infections but what is needed most is not new technology (adequate technology exists in the present) but encouragement and support in terms of guidelines and recommendations on UV technology from those authorities who have until recently been somewhat reticent and noncommittal on the matter.

1.10 UVGI and the Future of Disease Control

UVGI has a definite future in the control of contagious diseases and if applied on a widespread basis, it may be the key to controlling epidemics and pandemics. No other current technology has the capability, the adaptability, and the favorable economics to make it viable for an extremely wide variety of disease control applications. It is already used extensively and effectively in water applications and in surface disinfection applications. In combination with air filtration, it is the most effective and economic technology for disinfecting air. From health care applications to schools and residential environments, UVGI holds the promise of one day contributing in a major fashion to the eradication of many contagious diseases. The advent of multidrug-resistant microbes like MRSA and XTB, and emerging pathogens like SARS and Avian Influenza is likely to stimulate the increased use of UVGI systems in an ever wider number of applications. The contribution UV technology can make to the control of epidemics is amenable to analysis by the statistical models of epidemiology, which have demonstrated the potential for widespread use of UVGI systems to theoretically halt contagious airborne disease epidemics (Kowalski 2006). Perhaps continued research and development will ultimately lead to UVGI becoming a standard component of ventilation systems in all indoor environments and this age of airborne epidemics will come to an end.

References

Ager BP, Tickner JA. 1983. The control of microbiological hazards associated with air-conditioning and ventilation systems. Ann Occup Hyg 27(4):341–358.

Anderson K. 1959. *Pseudomonas pyocyanea* disseminated form an air cooling apparatus. Med J Aus 1:529.

Anderson WB, Huck PM, Dixon DG, Mayfield CI. 2003. Endotoxin inactivation in water by using medium-pressure UV lamps. Appl Environ Microbiol 69(5):3002–3004.

Asthana A, Tuveson RW. 1992. Effects of UV and phototoxins on selected fungal pathogens of citrus. Int J Plant Sci 153(3):442–452.

AWWA. 1971. Water Quality and Treatment. The American Water Works Association I, editor. New York: McGraw-Hill.

Banaszak EF, Thiede WH, Fink JN. 1970. Hypersensitivity pneumonitis due to contamination of an air conditioner. New England J Med 283(6):271–276.

Barnard J, Morgan H. 1903. The physical factors in phototherapy. Brit Med J 2:1269–1271.

Bedford THB. 1927. The nature of the action of ultra-violet light on micro-organisms. Brit J Exp Path 8:437–441.

Bolton JR, Cotton CA. 2008. Ultraviolet disinfection handbook. Denver, CO: American Water Works Association.

Buchbinder L, Phelps EB. 1941. Studies on microorganisms in simulated room environments. II. The survival rates of streptococci in the dark. J Bact 42:345–351.

Buttolph LJ, Haynes H. 1950. Ultraviolet Air Sanitation. Cleveland, OH: General Electric. Report nr LD-11.

CDC. 2003. Guidelines for environmental infection control in health-care facilities. MMWR 52(RR-10).

CDC. 2005. Guidelines for preventing the transmission of *Mycobacterium tuberculosis* in health-care facilities. In: CDC, editor. Federal Register. Washington: US Govt. Printing Office.

CIE. 2003. Ultraviolet Air Disinfection. Vienna, Austria: International Commission on Illumination. Report nr CIE 155:2003.
Coblentz WW, Stair R, Hogue JM. 1932. Spectral erythemic reaction of the untanned human skin to ultraviolet radiation. J Res Nat Bur Stand 8:541–547.
Cole WR, Bernard HR, Dunn B. 1964. Growth of bacteria on direct expansion air-conditioning coils. Surgery 55(3):436–439.
DelMundo F, McKhann CF. 1941. Effect of ultra-violet irradiation of air on incidence of infections in an infant's hospital. Am J Dis Child 61:213–225.
Downes A, Blunt TP. 1877. Research on the effect of light upon bacteria and other organisms. Proc Roy Soc London 26:488–500.
Ehrismann O, Noethling W. 1932. Uber die bactericide wirkung monochromatischen lichtes. Ztschr Hyg Infektionskr 113:597–628.
ELP. 2000. How UV-C lamps saved one company $58,000. Electric Light & Power 78(2).
Escombe A, Moore D, Gilman R, Navincopa M, Ticona E, Mitchell B, Noakes C, Martinez C, Sheen P, Ramirez R and others. 2009. Upper-room ultraviolet light and negative air ionization to prevent tuberculosis transmission. PLoS Med 6(3):312–322.
FEMA. 2003. Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings: Federal Emergency Management Agency. Report nr FEMA 426.
Finsen N. 1900. Die Resultate der Behandlung des lupus vulgaris durch knzentrierte chemische Lichtstrahlen. Allg Wien Med Z A5:60–65.
Fizeau H, Foucault L. 1843. Observations concernant l'action des rayons rouges sur les plaques degueeriennes. C R Habd Seances Acad Sci 23:679–682.
Fulton HR, Coblentz WW. 1929. The fungicidal action of ultraviolet radiation. J Agric Res 38:159.
Gates FL. 1929. A study of the bactericidal action of ultraviolet light. J Gen Physiol 13:231–260.
GE. 1950. Germicidal Lamps and Applications. USA: General Electric. Report nr SMA TAB: VIII-B.
Goldner JL, Allen BL. 1973. Ultraviolet light in orthopedic operating rooms at Duke University. Clin Ortho 96:195–205.
Goldner JL, Moggio M, Beissinger SF, McCollum DE. 1980. Ultraviolet light for the control of airborne bacteria in the operating room. In: Kundsin RB, editor. Airborne Contagion, Annals of the New York Academy of Sciences. New York: NYAS, pp. 271–284.
Grun L, Pitz N. 1974. U.V. radiators in humidifying units and air channels of air conditioning systems in hospitals. Zbl Bakt Hyg B159:50–60.
GSA. 2003. The Facilities Standards for the Public Buildings Service. Washington: Public Buildings Service of the General Services Administration.
Guha S, Bojarczuk N. 1998. Ultraviolet and violet GaN light emitting diodes on silicon. Appl Phys Lett 72:415.
Gunderman KO. 1980. Spread of microorganisms by air-conditioning systems – especially in hospitals. In: Kundsin RB, editor. Airborne Contagion. Boston: New York Academy of Sciences, pp.209–217.
Harstad JB, Decker HM, Wedum AG. 1954. Use of ultraviolet irradiation in a room air conditioner for removal of bacteria. Am Ind Hyg Assoc J 2:148–151.
Hart J. 1936. Sterilization of air in operating room by special bactericidal radiant energy. J Thoracic Surg 6:45–81.
Hart D. 1937. Operating room infections: preliminary report. Arch Surg 34:874–896.
Hart D, Sanger PW. 1939. Effect on wound healing of bactericidal ultraviolet radiation from a special unit: experimental study. Arch Surg 38(5):797–815.
Hausser K, Vahle W. 1927. Sonnenbrand und sonnenbraunung. In: Reiter T, Gabor D, editors. Zellteilung und Strahlung. Berlin: Springer, pp. 101–120.
Henle W, Sommer HE, Stokes J. 1942. Studies on air-borne infection in a hospital ward: II. Effects of ultra-violet irradiation and propylene glycol vaporization upon the prevention of experimental air-borne infection of mice by droplet nuclei. J Pediat 21:577–590.
Henri V. 1912. Comparison de l'action des rayons ultrav-violets sur les organismes avec les reactions photochemique simples et complexes. Compt Rend Soc Biol 73:323–325.

Henri V. 1914. Etude de l'action metabolique des rayons ultraviolets. CR Acad Sci (Paris) 159:340–343.
Higgons RA, Hyde GM. 1947. Effect of ultra-violet air sterilization upon incidence of respiratory infections in a children's institution. New York State J Med 47(7).
Hockberger P. 2002. A history of ultraviolet photobiology for humans, animals, and microorganisms. Photochem Photobiol 76(6):561–579.
Hollaender A. 1943. Effect of long ultraviolet and short visible radiation (3500 to 4900) on *Escherichia coli*. J Bact 46:531–541.
Kowalski WJ. 2006. Aerobiological Engineering Handbook: A Guide to Airborne Disease Control Technologies. New York: McGraw-Hill.
Kraissl CJ, Cimiotti JG, Meleney FL. 1940. Considerations in the use of ultra-violet radiation in operating rooms. Ann Surg 111:161–185.
Lorch W. 1987. Handbook of Water Purification. Chichester: Ellis Horwood Ltd.
Luciano JR. 1977. Air Contamination Control in Hospitals. New York: Plenum Press.
Luckiesh M, Taylor AH. 1925. Fading of colored materials in daylight and artificial light. Trans Illum Eng Soc 20:1078.
Luckiesh M, Holladay LL. 1942. Tests and data on disinfection of air with germicidal lamps. Gen Electric Rev 45(4):223–231.
Luckiesh M, Holladay LL. 1942a. Designing installations of germicidal lamps for occupied rooms. General Electric Review 45(6):343–349.
Luckiesh M. 1945. Disinfection with germicidal lamps: Air – II. Electrical World Oct.13:109 –111.
Luckiesh M. 1946. Applications of Germicidal, Erythemal and Infrared Energy. New York: D. Van Nostrand Co.
Martin S, Dunn C, Friehaut J, Bahnfleth W, Lau J, Nedeljkovic A. 2008. Ultraviolet germicidal irradiation: current best practices. ASHRAE J August:28–36.
Menzies D, Popa J, Hanley JA, Rand T, Milton DK. 2003. Effect of ultraviolet germicidal lights installed in office ventilation systems on workers′ health and wellbeing: double-blind multiple crossover trials. The Lancet 362(November 29):1785–1791.
MRC. 1954. Air Disinfection with Ultra-violet Irradiation; Its Effect on Illness among School-Children by the Air Hygiene Committee. London: Medical Research Council, Her Majesty's Stationary Office. Report nr 283.
Nardell EA. 1988. Chapter 12: Ultraviolet air disinfection to control tuberculosis. In: Kundsin RB, editor. Architectural Design and Indoor Microbial Pollution. New York: Oxford University Press, pp. 296–308.
Newcomer H. 1917. The abiotic action of ultraviolet light. J Exp Med 26:841.
Overholt RH, Betts RH. 1940. A comparative report on infection of thoracoplasty wounds. J Thoracic Surg 9:520–529.
Perkins JE, Bahlke AM, Silverman HF. 1947. Effect of ultra-violet irradiation of classrooms on the spread of measles in large rural central schools. Am J Pub Health 37:529–537.
Philips. 1985. UVGI Catalog and Design Guide. Netherlands: Catalog No. U.D.C. 628.9.
Prat S. 1936. Strahlung und antagonistische wirkungen. Protoplasma 26:113–149.
Rentschler HC, Nagy R. 1940. Advantages of bactericidal ultraviolet radiation in air conditioning systems. HPAC 12:127–130.
Renz C. 1921. Photo-reactions of the oxides of titanium, cerium, and earth-acids. Helv Chim Acta 4:961.
Riley R, Wells W, Mills C, Nyka W, McLean R. 1957. Air hygiene in tuberculosis: Quantitative studies of infectivity and control in a pilot ward. Am Rev Tuberc Pulmon 75:420–431.
Riley RL, O'Grady F. 1961. Airborne Infection. New York: The Macmillan Company.
Riley RL. 1972. The ecology of indoor atmospheres: Airborne infection in hospitals. J Chron Dis 25:421–423.
Riley RL. 1980. Part I. History and epidemiology: Historical background. In: Kundsin RB, editor. Airborne Contagion, Annals of the New York Academy of Sciences. New York: NYAS, pp. 1–9.

Riley RL. 1980a. Prevention and control of airborne infection in the community. In: Kundsin RB, editor. Airborne Contagion, Annals of the New York Academy of Sciences. New York: NYAS, pp. 331–339.
Ritter M, Olberding E, Malinzak R. 2007. Ultraviolet lighting during orthopaedic surgery and the rate of infection. J Bone Joint Surg 89:1935–1940.
Rivers T, Gates F. 1928. Ultra-violet light and vaccine virus. II. The effect of monochromatic ultra-violet light upon vaccine virus. J Exp Med 47:45–49.
Robertson EC, Doyle ME, Tisdall FF, Koller LR, Ward FS. 1939. Air contamination and air sterilization. Am J Dis Child 58:1023–1037.
Scheir R. 2000. Electric utility solves IAQ problem with UVC electrical energy. HPAC Eng 69(5):28–29, 85, 87.
Schicht HH. 1972. The diffusion of micro-organisms by air conditioning installations. The Steam and Heating Engineer October:6–13.
Schneiter R, Hollaender A, Caminita BH, Kolb RW, Fraser HF, duBuy HG, Neal PA, Rosenblum HG. 1944. Effectiveness of ultra-violet irradiation of upper air for the control of bacterial air contamination in sleeping quarters. Am J Hyg 40:136.
Shantha T, Sreenivasa M. 1977. Photo-destruction of aflatoxin in groundnut oil. Indian J Technol 15:453.
Sharp G. 1940. The effects of ultraviolet light on bacteria suspended in air. J Bact 38:535–547.
Sommer HE, Stokes J. 1942. Studies on air-borne infection in a hospital ward. J Pediat 21:569–576.
Spendlove JC, Fannin KF. 1983. Source, significance, and control of indoor microbial aerosols: Human health aspects. Public Health Rep 98(3):229–244.
USACE. 2000. Guidelines on the Design and Operation of HVAC Systems in Disease Isolation Areas. U.S. Army Center for Health Promotion and Preventive Medicine. Report nr TG252.
von Recklinghausen M. 1914. The Ultra-Violet rays and their application for the sterilization of water. J Franklin Institute 1057–1062:681–704.
Walter CW. 1969. Ventilation and air conditioning as bacteriologic engineering. Anesthesiology 31:186–192.
Ward M. 1892. Experiments of the action of light on *Bacillus anthracis*. Proc Roy Soc Lond 52:393–403.
Wells W, Wells M. 1936. Air-borne infection. JAMA 107:1698–1703.
Wells WF. 1938. Air-borne infections. Mod Hosp 51:66–69.
Wells WF. 1940. Bactericidal irradiation of air, physical factors. J Franklin Inst 229:347–372.
Wells WF, Wells MW, Wilder TS. 1942. The environmental control of epidemic contagion; I – An epidemiologic study of radiant disinfection of air in day schools. Am J Hyg 35:97–121.
Wells WF. 1943. Air disinfection in day schools. Am J Pub Health 33:1436–1443.
Wells WF, Holla WA. 1950. Ventilation in flow of measles and chickenpox through community. Progress report, Jan. 1, 1946 to June 15, 1949, airborne infection study. J Am Med Assoc 142:1337–1344.
Wheeler SM, Ingraham HS, Hollaender A, Lill ND, Gershon-Cohen J, Brown EW. 1945. Ultra-violet light control of airborne infections in a naval training center. Am J Pub Health 35:457–468.
Whitby G, Scheible O. 2004. The history of UV and wastewater. IUVA News 6(3):15–26.
WHO. 1999. Guidelines for the Prevention of Tuberculosis in Health Care Facilities in Resource Limited Settings. Geneva: World Health Organization. Report nr WHO/CDS/TB/99.269.
Whyte W. 1968. Bacteriological aspects of air-conditioning plants. J Hyg 66:567–584.
Widmark E. 1889. Uber den einfluss des lichtes auf die haut. Hygiea 3:1–23.
Widmark J. 1889a. De l'influence de la lumiere sur la peau. Biol Foren Forhandl Verhandlungen Biolog Vereins 1:9–13, 131–134.
Zeterberg JM. 1973. A review of respiratory virology and the spread of virulent and possibly antigenic viruses via air conditioning systems. Ann Allergy 31:228–299.

Chapter 2

UVGI Disinfection Theory

2.1 Introduction

Ultraviolet Germicidal Irradiation (UVGI) is electromagnetic radiation that can destroy the ability of microorganisms to reproduce by causing photochemical changes in nucleic acids. Wavelengths in the UVC range are especially damaging to cells because they are absorbed by nucleic acids. The germicidal effectiveness of UVC peaks at about 260–265 nm. This peak corresponds to the peak of UV absorption by bacterial DNA. The germicidal effectiveness of UVC radiation can vary between species and the broader range wavelengths that include UVB also make a small contribution to inactivation (Webb and Tuveson 1982). Although the methods and details of disinfection with ultraviolet light are fairly well understood, to the point that effective disinfection systems can be designed and installed with predictable effects, the exact nature of the effect of ultraviolet light on microorganisms at the molecular level is still a matter of intensive research. This chapter examines the fundamentals of the complex interaction between UV irradiation and cell DNA at the molecular level and provides detailed background information to aid in the understanding of the various biophysical processes that are involved in microbial inactivation.

2.2 UV Inactivation

The spectrum of ultraviolet light extends from wavelengths of about 100–400 nm. The subdivisions of most interest include UVC (200–280 nm), and UVB (280–320 nm). Although all UV wavelengths cause some photochemical effects, wavelengths in the UVC range are particularly damaging to cells because they are absorbed by proteins, RNA, and DNA (Bolton and Cotton 2008, Rauth 1965). The germicidal effectiveness of UVC is illustrated in Fig. 2.1, where it can be observed that germicidal efficiency reaches a peak at about 260–265 nm. This corresponds to the peak of UV absorption by bacterial DNA (Harm 1980). The germicidal effectiveness of UVC and UVB wavelengths can vary between species. Low pressure

W. Kowalski, *Ultraviolet Germicidal Irradiation Handbook*,
DOI 10.1007/978-3-642-01999-9_2, © Springer-Verlag Berlin Heidelberg 2009