Delmar HEALTH CARE

Clinical Application of MECHANICAL VENTILATION

Fourth Edition

David W. Chang

Clinical Application of MECHANICAL VENTILATION

David W. Chang

Clinical Application of MECHANICAL VENTILATION

Fourth Edition

David W. Chang, Ed.D., RRT–NPS

Professor
Department of Cardiorespiratory Care
University of South Alabama
Mobile, Alabama

DELMAR
CENGAGE Learning

Australia • Brazil • Japan • Korea • Mexico • Singapore • Spain • United Kingdom • United States

DELMAR
CENGAGE Learning

Clinical Application of Mechanical Ventilation, Fourth Edition
David W. Chang

Vice President, Careers & Computing: Dave Garza

Publisher, Health Care: Stephen Helba

Associate Acquisitions Editor: Christina Gifford

Director, Development–Careers & Computing: Marah Bellegarde

Product Development Manager, Careers: Juliet Steiner

Associate Product Manager: Meghan E. Orvis

Editorial Assistant: Cassie Cloutier

Executive Brand Manager: Wendy Mapstone

Market Development Manager: Jonathan Sheehan

Senior Production Director: Wendy Troeger

Production Manager: Andrew Crouth

Senior Content Project Manager: Kara A. DiCaterino

Senior Art Director: David Arsenault

Cover Image:
© Icons Jewelry/www.shutterstock.com
© Sebastian Kaulitzki/www.shutterstock.com

Library of Congress Control Number: 2012953799

ISBN-13: 978-1-1115-3958-0

ISBN-10: 1-1115-3958-8

Delmar
5 Maxwell Drive
Clifton Park, NY 12065-2919
USA

Cengage Learning is a leading provider of customized learning solutions with office locations around the globe, including Singapore, the United Kingdom, Australia, Mexico, Brazil, and Japan. Locate your local office at: **international.cengage.com/region**

Cengage Learning products are represented in Canada by Nelson Education, Ltd.

To learn more about Delmar, visit **www.cengage.com/delmar**

Purchase any of our products at your local college store or at our preferred online store **www.cengagebrain.com**

Printed in the United States of America
1 2 3 4 5 6 7 17 16 15 14 13

Dedicated with love
to my wife, Bonnie and our children,
Michelle, Jennifer, and Michael
for their support in my professional endeavors
and personal leisure activities

Contents

Preface xxvi
Acknowledgments xxx

CHAPTER 1: PRINCIPLES OF MECHANICAL VENTILATION

Introduction 2
Airway Resistance 3
Factors Affecting Airway Resistance 3
Airway Resistance and the Work of Breathing (ΔP) 4
Effects on Ventilation and Oxygenation 5
Airflow Resistance 5
Lung Compliance 6
Compliance Measurement 6
Static and Dynamic Compliance 7
Compliance and the Work of Breathing 10
Effects on Ventilation and Oxygenation 10
Deadspace Ventilation 10
Anatomic Deadspace 11
Alveolar Deadspace 11
Physiologic Deadspace 11
Ventilatory Failure 12
Hypoventilation 12
Ventilation/Perfusion (V/Q) Mismatch 13
Intrapulmonary Shunting 14
Diffusion Defect 15
Oxygenation Failure 16
Hypoxemia and Hypoxia 17
Clinical Conditions Leading to Mechancial Ventilation 18
Depressed Respiratory Drive 18
Excessive Ventilatory Workload 18
Failure of Ventilatory Pump 19

Summary 21
Self-Assessment Questions 21
Answers to Self-Assessment Questions 24
References 24
Additional Resources 25

CHAPTER 2: EFFECTS OF POSITIVE PRESSURE VENTILATION

Introduction 27
Pulmonary Considerations 28
Spontaneous Breathing 28
Positive Pressure Ventilation 28
Airway Pressures 29
Compliance 30
Cardiovascular Considerations 30
Mean Airway Pressure and Cardiac Output 30
Decrease in Cardiac Output and O_2 Delivery 31
Blood Pressure Changes 31
Pulmonary Blood Flow and Thoracic Pump Mechanism 32
Hemodynamic Considerations 34
Positive Pressure Ventilation 34
Positive End-Expiratory Pressure 34
Renal Considerations 35
Renal Perfusion 35
Indicators of Renal Failure 36
Effects of Renal Failure on Drug Clearance 36
Hepatic Considerations 38
PEEP and Hepatic Perfusion 38
Indicators of Liver Dysfunction 38
Effects of Decreased Hepatic Perfusion on Drug Clearance 38
Abdominal Considerations 39
Effects of PEEP and Increased Intra-Abdominal Pressure 39
Gastrointestinal Considerations 40
Nutritional Considerations 40
Muscle Fatigue 41
Diaphragmatic Dysfunction 41
Nutritional Support 41
Nutrition and the Work of Breathing 42
Neurologic Considerations 43
Hyperventilation 43
Ventilatory and Oxygenation Failure 44
Indicators of Neurologic Impairment 44
Summary 45
Self-Assessment Questions 45
Answers to Self-Assessment Questions 48
References 48

CHAPTER 3: CLASSIFICATION OF MECHANICAL VENTILATORS

Introduction 51
Ventilator Classification 52
Ventilatory Work 52
Input Power 53
Drive Mechanism 53
Piston Drive Mechanism 54
Bellows Drive Mechanism 55
Microprocessor-Controlled Pneumatic Drive Mechanism 55
Control Circuit 56
Mechanical 56
Pneumatic 56
Fluidics 56
Electronic 57
Control Variables 57
Pressure Controller 57
Volume Controller 59
Flow Controller 59
Time Controller 59
Phase Variables 60
Trigger Variable 60
Limit Variable 61
Cycle Variable 62
Baseline Variable 62
Conditional Variable 63
Terminology of Ventilation Modes 66
Volume-Controlled Ventilation 66
Pressure-Controlled Ventilation 66
Intermittent Mandatory Ventilation (IMV) 67
Pressure Support 67
Dual Control within a Breath 68
Dual Control Breath-to-Breath 68
Pressure-Limited Time-Cycled Breaths 68
Pressure-Limited Flow-Cycled Breaths 68
Automode 69
Proportional Assist Ventilation 69
Automatic Tube Compensation 69
Airway Pressure Release Ventilation 70
Output Waveforms 70
Pressure Waveforms 72
Volume Waveforms 73
Flow Waveforms 74
Alarm Systems 75
Input Power Alarms 75

Control Circuit Alarms	75
Output Alarms	76
Summary	76
Self-Assessment Questions	77
Answers to Self-Assessment Questions	78
References	78
Additional Resources	79

CHAPTER 4: OPERATING MODES OF MECHANICAL VENTILATION

Introduction	82
Negative and Positive Pressure Ventilation	82
Negative Pressure Ventilation	83
Positive Pressure Ventilation	84
Operating Modes of Mechanical Ventilation	84
Closed-Loop System	86
Spontaneous	86
Apnea Ventilation	87
Positive End-Expiratory Pressure (PEEP)	87
Indications for PEEP	87
Physiology of PEEP	89
Complications of PEEP	89
Continuous Positive Airway Pressure (CPAP)	91
Bilevel Positive Airway Pressure (BiPAP)	91
Indications for BiPAP	91
Initial Settings	92
Adjustments of IPAP and EPAP	92
Controlled Mandatory Ventilation (CMV)	92
Indications for Control Mode	93
Complications of Control Mode	94
Assist/Control (AC)	94
Assist Control Triggering Mechanism	94
Assist Control Cycling Mechanism	95
Indications for AC Mode	95
Advantages of AC Mode	96
Complications of AC Mode	96
Intermittent Mandatory Ventilation (IMV)	96
Synchronized Intermittent Mandatory Ventilation (SIMV)	97
SIMV Mandatory Breath-Triggering Mechanism	97
SIMV Spontaneous Breath-Triggering Mechanism	98
Indications for SIMV Mode	99
Advantages of SIMV Mode	99
Complications of SIMV Mode	100
Mandatory Minute Ventilation (MMV)	100
Pressure Support Ventilation (PSV)	102
Indications for PSV Mode	103
Adaptive Support Ventilation (ASV)	104

Proportional Assist Ventilation (PAV) 105
Volume-Assured Pressure Support (VAPS) 106
Pressure-Regulated Volume Control (PRVC) 107
Automode 108
Adaptive Pressure Control (APC) 108
Volume Ventilation Plus (VV+) 108
Volume Control Plus (VC+) 109
Volume Support (VS) 109
Pressure-Controlled Ventilation (PCV) 109
Airway Pressure Release Ventilation (APRV) 111
Indications for APRV 112
Biphasic Positive Airway Pressure (Biphasic PAP) 112
Inverse Ratio Ventilation (IRV) 113
Physiology of IRV 113
Adverse Effects of IRV 114
Pressure Control-IRV (PC-IRV) 114
Automatic Tube Compensation (ATC) 115
Neurally Adjusted Ventilatory Assist (NAVA) 115
High-Frequency Oscillatory Ventilation (HFOV) 115
Summary 116
Self-Assessment Questions 116
Answers to Self-Assessment Questions 119
References 119
Additional Resources 123

CHAPTER 5: SPECIAL AIRWAYS FOR VENTILATION

Introduction 126
Oropharyngeal Airway 126
Types of Oropharyngeal Airways 126
Selection of Oropharyngeal Airway 127
Insertion of Oropharyngeal Airway 128
Nasopharyngeal Airway 128
Selection of Nasopharyngeal Airway 129
Insertion of Nasopharyngeal Airway 129
Complications of Nasopharyngeal Airway 130
Esophageal Obturator Airway (EOA) 130
Insertion of EOA 131
Esophageal Gastric Tube Airway (EGTA) 132
Laryngeal Mask Airway (LMA) 133
Use of LMA 133
Contraindications for LMA 134
Selection of LMA 135
Insertion of LMA 135
Removal of LMA 136
Limitations of LMA 138

Esophageal-Tracheal Combitube (ETC) 139
Insertion and Use of ETC 139
Complications of ETC 140
Double-Lumen Endobronchial Tube (DLT) 140
Indications 141
Selection of DLT 142
Insertion of DLT 142
Complications of DLT 143
Summary 144
Self-Assessment Questions 144
Answers to Self-Assessment Questions 146
References 146
Additional Resources 149

CHAPTER 6: AIRWAY MANAGEMENT IN MECHANICAL VENTILATION

Introduction 151
Intubation 152
Indications 153
Common Artificial Airways in Mechanical Ventilation 154
Endotracheal Tube 154
Tracheostomy Tube 155
Specialty Tracheostomy Devices 155
Intubation Procedure 156
Preintubation Assessment and Signs of Difficult Airway 156
Supplies 157
Special Visualization Devices 161
Selection of Endotracheal Tube 162
Ventilation and Oxygenation 162
Oral Intubation 163
Nasal Intubation 163
Common Errors 163
Signs of Endotracheal Intubation 165
Signs of Esophageal Intubation 167
Rapid Sequence Intubation 168
Indications and Contraindications 168
Practice Guidelines 168
Management of Endotracheal and Tracheostomy Tubes 171
Securing Endotracheal and Tracheostomy Tubes 171
Cuff Pressure 171
Minimal Occlusion Volume and Minimal Leak Technique 172
Endotracheal Suctioning 173
Endotracheal Tube Changer 175
Speaking Valves 177
Contraindications 177
Safety Requirements 177

Positive Pressure Ventilation 178
Extubation 179
Predictors of Successful Extubation 179
Procedure 179
Unplanned Extubation 181
Complications of EndotracheaL Airway 182
During Intubation 183
While Intubated 183
Immediately after Extubation 183
Following Extubation 184
Summary 184
Self-Assessment Questions 184
Answers to Self-Assessment Questions 187
References 188
Additional Resources 191

CHAPTER 7: NONINVASIVE POSITIVE PRESSURE VENTILATION

Introduction 193
Terminology 194
Physiologic Effects of NPPV 194
Use of Continuous Positive Airway Pressure (CPAP) 195
Obstructive Sleep Apnea 196
Use of Bilevel Positive Airway Pressure (Bilevel PAP) 197
Common Interfaces for CPAP and Bilevel PAP 198
Nasal Mask 198
Oronasal Mask 200
Nasal Pillows 200
Full-Face Mask 202
Potential Problems with Interfaces 203
Titration of Continuous Positive Airway Pressure 203
Autotitration 203
Ramp 204
C-Flex™ 204
Titration of Bilevel Positive Airway Pressures 204
Bi-Flex™ 205
Summary 206
Self-Assessment Questions 206
Answers to Self-Assessment Questions 208
References 208
Additional Resources 211

CHAPTER 8: INITIATION OF MECHANICAL VENTILATION

Introduction 213
Goals of Mechanical Ventilation 213

Indications 214
Acute Ventilatory Failure 214
Impending Ventilatory Failure 215
Severe Hypoxemia 217
Prophylactic Ventilatory Support 218
Contraindications 218
Initial Ventilator Settings 220
Mode 220
Dual Control Mode 220
Frequency 221
Tidal Volume 222
Pressure Support 223
F_IO_2 224
PEEP 225
I:E Ratio 225
Flow Pattern 227
Ventilator Alarm Settings 229
Low Exhaled Volume Alarm 229
Low Inspiratory Pressure Alarm 229
High Inspiratory Pressure Alarm 229
Apnea Alarm 230
High Frequency Alarm 230
High and Low F_IO_2 Alarms 230
Hazards And Complications 230
Types of Hazards and Complications 231
Malfunction and Misuse of Alarms 232
Barotrauma 232
Decrease in Cardiac Output and Blood Pressure 232
Summary 234
Self-Assessment Questions 235
Answers to Self-Assessment Questions 238
References 238
Additional Resources 240

CHAPTER 9: MONITORING IN MECHANICAL VENTILATION

Introduction 242
Vital Signs 243
Heart Rate 243
Blood Pressure 243
Respiratory Frequency 244
Temperature 245
Chest Inspection 246
Chest Movement 246
Auscultation 248
Imaging 251

Fluid Balance and Anion Gap 253
Fluid Balance 253
Anion Gap 253
Arterial Blood Gases 254
Assessment of Ventilatory Status 255
Assessment of Oxygenation Status 255
Limitations of Blood Gases 257
Oxygen Saturation Monitoring 258
Pulse Oximetry 258
Accuracy and Clinical Use of Pulse Oximetry 259
Limitations of Pulse Oximetry 259
Integrated Pulse CO-Oximetry 259
End-Tidal Carbon Dioxide Monitoring 260
Capnography 261
Capnography Waveforms and Clinical Application 261
$P(a\text{-}et)CO_2$ Gradient 264
Limitations of Capnography Monitoring 264
Transcutaneous Blood Gas Monitoring 265
Transcutaneous PO_2 ($PtcO_2$) 265
Transcutaneous PCO_2 ($PtcCO_2$) 266
Cerebral Perfusion Pressure 266
Summary 267
Self-Assessment Questions 267
Answers to Self-Assessment Questions 270
References 270

CHAPTER 10: HEMODYNAMIC MONITORING

Introduction 276
Invasive Hemodynamic Monitoring 276
Technical Background 276
Units of Measurement 277
Types of Catheters 277
Arterial Catheter 277
Insertion of Arterial Catheter 278
Normal Arterial Pressure and Mean Arterial Pressure 279
Pulse Pressure 279
Potential Problems with Arterial Catheter 281
Central Venous Catheter 281
Insertion of Central Venous Catheter 282
Components of Central Venous Pressure Waveform 283
CVP Measurements 284
Pulmonary Artery Catheter 284
Insertion of Pulmonary Artery Catheter 285
Components of Pulmonary Arterial Pressure Waveform 286
PAP Measurements 286

Pulmonary Capillary Wedge Pressure 289
Components of Pulmonary Capillary Wedge Pressure Waveform 289
PCWP Measurements 290
Verification of the Wedged Position 291
Cardiac Output and Cardiac Index 291
Summary of Preloads and Afterloads 292
Calculated Hemodynamic Values 292
Stroke Volume and Stroke Volume Index 293
Oxygen Consumption and Oxygen Consumption Index 293
Pulmonary Vascular Resistance 293
Systemic Vascular Resistance 293
Mixed Venous Oxygen Saturation 294
Decrease in Mixed Venous Oxygen Saturation 294
Increase in Mixed Venous Oxygen Saturation 294
Less-Invasive Hemodynamic Monitoring 295
Pulse Contour Analysis 295
Noninvasive Hemodynamic Monitoring 296
Transesophageal Echocardiography 296
Carbon Dioxide Elimination ($\dot{V}CO_2$) 297
Impedance Cardiography 297
Theory of Operation 298
Thermodilution Method and ICG 298
Accuracy of ICG 300
Clinical Application 300
Summary 301
Self-Assessment Questions 301
Answers to Self-Assessment Questions 303
References 304

CHAPTER 11: VENTILATOR WAVEFORM ANALYSIS

Introduction 309
Flow Waveforms During Positive Pressure Ventilation 311
Effects of Constant Flow During Volume-Controlled Ventilation 312
Flow-Time Waveform 313
Pressure-Time Waveform 314
Controlled Mandatory Ventilation 317
Assist Mandatory Volume-Controlled Ventilation 318
Mathematical Analysis of Constant-Flow Ventilation 320
Spontaneous Ventilation During Mechanical Ventilation 323
Synchronized Intermittent Mandatory Ventilation 323
Continuous Positive Airway Pressure 325
Effects of Flow, Circuit, and Lung Characteristics on Pressure-Time Waveforms 326
Flow and Transairway Pressure 326
Compliance and Alveolar Pressure 327

Effects of Descending Ramp Flow Waveform during Volume-Controlled Ventilation 328
Time- and Flow-Limited Ventilation 328
Peak Flow and Tidal Volume Relationship in Time-Limited Ventilation 333
Effects of End-Flow on End-Transairway Pressure 334
Distribution of Delivered Tidal Volume 334
CMV during Descending Ramp Flow Ventilation 336
Waveforms Developed during Pressure-Controlled Ventilation 337
Pressure-Controlled Ventilation (PCV) 337
Assist Breaths during Pressure-Controlled Ventilation 338
Inverse Ratio Pressure-Controlled Ventilation (IRPCV) 338
Pressure Support and Spontaneous Ventilation 340
Pressure Support Ventilation (PSV) 340
Adjusting Rise Time during PSV 341
SIMV (CFW) and PSV 342
SIMV (DRFW) and PSV 343
Effects of Lung Characteristics on Pressure-Controlled Ventilation Waveforms 343
Using Waveforms for Patient-Ventilator System Assessment 345
Patient-Ventilator Dyssynchrony 345
Dyssynchrony during Constant Flow Ventilation 347
Dyssynchrony during Descending Ramp Flow Ventilation 349
Changes in Pressure Waveforms during Respiratory Mechanics Measurement 350
Dyssynchrony during Pressure-Controlled Ventilation 351
Using Expiratory Flow and Pressure Waveforms as Diagnostic Tools 352
Increased Airway Resistance 352
Loss of Elastic Recoil 354
Decreased Lung-Thorax Compliance (C_{LT}) 355
Gas Trapping and Uncounted Breathing Efforts 356
Troubleshooting Ventilator Function 357
Lack of Ventilator Response 357
Circuit Leaks 358
Pressure-Volume Loop (PVL) and Flow-Volume Loop (FVL) 359
Pressure-Volume Loop (PVL) 359
Effects of Lung-Thorax Compliance on PVL 360
Effect of Airflow Resistance on PVL 361
Lower Inflection Point on PVL and Titration of PEEP 361
Upper Inflection Point on PVL and Adjustment of V_T 363
Effects of Airway Status on Flow-Volume Loop (FVL) 363
Summary 364
Self-Assessment Questions 365
Answers to Self-Assessment Questions 370
References 370
Additional Resources 371

CHAPTER 12: MANAGEMENT OF MECHANICAL VENTILATION

Introduction 375
Basic Management Strategies 375
Strategies to Improve Ventilation 376
Increase Ventilator Frequency 376
Increase Spontaneous Tidal Volume or Frequency 377
Increase Ventilator Tidal Volume 378
Other Strategies to Improve Ventilation 378
Permissive Hypercapnia 378
Strategies to Improve Oxygenation 380
Increase Inspired Oxygen Fraction (F_IO_2) 380
Improve Ventilation and Reduce Mechanical Deadspace 381
Improve Circulation 382
Maintain Normal Hemoglobin Level 382
Initiate Continuous Positive Airway Pressure (CPAP) 383
Initiate Positive End-Expiratory Pressure (PEEP) 383
Initiate Inverse Ratio Ventilation (IRV) 384
Initiate Extracorporeal Membrane Oxygenation (ECMO) 384
Initiate High Frequency Oscillatory Ventilation (HFOV) for Adults 385
Arterial Blood Gases 386
Respiratory Acidosis and Compensated Metabolic Alkalosis 387
Respiratory Alkalosis and Compensated Metabolic Acidosis 387
Alveolar Hyperventilation Due to Hypoxia, Improper Ventilator Settings, or Metabolic Acidosis 388
Alveolar Hyperventilation in Patients with COPD 388
Alveolar Hypoventilation Due to Sedation or Patient Fatigue 389
Metabolic Acid-Base Abnormalities 389
Troubleshooting of Common Ventilator Alarms and Events 389
Low Pressure Alarm 389
Low Expired Volume Alarm 390
High Pressure Alarm 391
High Frequency Alarm 391
Apnea/Low Frequency Alarm 392
High PEEP Alarm 392
Low PEEP Alarm 392
Auto-PEEP 393
Care of the Ventilator Circuit 394
Circuit Compliance 395
Circuit Patency 395
Humidity and Temperature 396
Frequency of Circuit Change 397
Care of the Artificial Airway 397
Patency of the Endotracheal Tube 397
Humidification and Removal of Secretions 398

Ventilator-Associated Pneumonia 399
Fluid Balance 400
Distribution of Body Water 400
Clinical Signs of Extracellular Fluid Deficit or Excess 401
Treatment of Extracellular Fluid Abnormalities 402
Electrolyte Balance 402
Normal Electrolyte Balance 402
Sodium Abnormalities 403
Potassium Abnormalities 404
Nutrition 405
Undernutrition 405
Overfeeding 406
Low-Carbohydrate High-Fat Diet 406
Total Caloric Requirements 407
Phosphate Supplement 407
Adjunctive Management Strategies 408
Low Tidal Volume 408
Prone Positioning 409
Tracheal Gas Insufflation 410
Summary 411
Self-Assessment Questions 412
Answers to Self-Assessment Questions 415
References 415
Additional Resources 419

CHAPTER 13: PHARMACOTHERAPY FOR MECHANICAL VENTILATION

Introduction 421
Drugs for Improving Ventilation 422
Autonomic Nervous System Agents 422
Adrenergic Bronchodilators (Sympathomimetics) 423
Anticholinergic Bronchodilators (Parasympatholytics) 426
Xanthine Bronchodilators 427
Anti-Inflammatory Agents (Corticosteroids) 429
Delivery of MDI Medications 430
Neuromuscular Blocking Agents 431
Mechanism of Action 432
Characteristics of Neuromuscular Blocking Agents 433
Factors Affecting Neuromuscular Blockade 433
Adverse Effects 436
Evaluation of Neuromuscular Blockade 437
Central Nervous System Agents 439
Sedatives and Antianxiety Agents (Benzodiazepines) 440
Opioid Analgesics 442
Agents for Seizures and Elevated Intracranial Pressure (Barbiturates) 447

Other Agents Used in Mechanical Ventilation 448
Propofol 449
Haloperidol 449
Dexmedetomidine 451
Nitric Oxide 452
Summary 454
Self-Assessment Questions 454
Answers to Self-Assessment Questions 456
References 457
Additional Resources 460

CHAPTER 14: PROCEDURES RELATED TO MECHANICAL VENTILATION

Introduction 462
Chest Tube and Drainage System 462
Indications for Chest Tube 463
Chest Tube Selection and Placement 463
Methods of Placement 465
Chest Tube Drainage System 466
Care and Removal of Chest Tube 469
Transport with Chest Tube 469
Assisting in Fiberoptic Bronchoscopy 470
Indications for Fiberoptic Bronchoscopy 470
Bronchoscope and Medications 472
Insertion of Bronchoscope 473
Types of Specimen 475
Complications 476
Postbronchoscopy Care 477
Transport of Mechanically Ventilated Patients 477
Indications 478
Contraindications 478
Equipment and Supplies 478
Types of Transport 478
Procedures for Interhospital Transport 480
Hazards and Complications 481
Magnetic Resonance Imaging 481
Summary 482
Self-Assessment Questions 483
Answers to Self-Assessment Questions 484
References 485
Additional Resources 488

CHAPTER 15: CRITICAL CARE ISSUES IN MECHANICAL VENTILATION

Introduction 490
Acute Lung Injury and Acute Respiratory Distress Syndrome 490

Definitions of ALI and ARDS 491
Pathophysiology 492
Clinical Presentations 493
Lung Protection Using Airway Pressure Thresholds 494
Low Tidal Volume and Permissive Hypercapnia 494
Decremental Recruitment Maneuver to Determine Optimal PEEP 495
Prone Positioning 496
Ventilator-Associated Pneumonia (VAP) 497
Incidence of VAP 497
Clinical Presentations 498
Prevention of VAP 499
Treatment of VAP 501
Hypoxic-Ischemic Encephalopathy (HIE) 501
General Principles of HIE 502
Cerebral Perfusion Pressure 503
Decrease in CPP Due to Cardiac Arrest 503
Decrease in CPP Due to Shock 504
Decrease in CPP Due to Brain Injury 504
Evaluation and Treatment of HIE 504
Trauma Brain Injury 505
Delayed Brain Injury 505
Acceleration and Deceleration Brain Injuries 506
Clinical Evaluation and Assessment 506
Management Strategies 507
Respiratory Management 508
Summary 509
Self-Assessment Questions 509
Answers to Self-Assessment Questions 511
References 511

CHAPTER 16: WEANING FROM MECHANICAL VENTILATION

Introduction 517
Definition of Weaning Success and Failure 517
Weaning Success 518
Weaning in Progress 518
Weaning Failure 518
Patient Condition Prior to Weaning 519
Weaning Criteria 520
Ventilatory Criteria 520
Oxygenation Criteria 522
Pulmonary Reserve 524
Pulmonary Measurements 524
Rapid Shallow Breathing Index (RSBI) 526
Weaning Procedure 527
Spontaneous Breathing Trial 527

Failure of SBT 527
Pressure Support Ventilation 527
Other Modes of Partial Ventilatory Support 529
Weaning Protocol 530
Signs of Weaning Failure 531
Causes of Weaning Failure 533
Increase of Airflow Resistance 533
Decrease of Compliance 533
Respiratory Muscle Fatigue 533
Terminal Weaning 534
Prior to Withdrawal 535
Withdrawal 536
Summary 536
Self-Assessment Questions 536
Answers to Self-Assessment Questions 539
References 539
Additional Resources 542

CHAPTER 17: NEONATAL MECHANICAL VENTILATION

Introduction 545
Intubation 546
Indications 546
Equipment 547
Surfactant Replacement Therapy 548
History 548
Indications 549
Types of Surfactant and Dosages 549
Outcomes 551
Nasal CPAP 552
Use of Nasal CPAP 552
Basic Principles of Neonatal Ventilation 553
Pressure-Controlled Ventilation 553
Volume-Controlled Ventilation 553
Ventilator Circuits and Humidifiers 553
Initiation of Neonatal Ventilatory Support 555
Indications for Mechanical Ventilation 555
Initial Ventilator Settings 556
High Frequency Ventilation (HFV) 558
High Frequency Positive Pressure Ventilation (HFPPV) 559
High Frequency Jet Ventilation (HFJV) 560
High Frequency Oscillatory Ventilation (HFOV) 561
Initial HFOV Settings 564
Other Methods of Ventilation 566
Machine Volume 567

Volume Guarantee	567
Liquid Ventilation	567
Extracorporeal Membrane Oxygenation (ECMO)	568
History	568
Patient Selection	568
ECMO Criteria	569
Mechanisms of Bypass	570
Complications	570
Summary	572
Self-Assessment Questions	572
Answers to Self-Assessment Questions	576
References	576
Additional Resources	579

CHAPTER 18: MECHANICAL VENTILATION IN NONTRADITIONAL SETTINGS

Introduction	581
Mechanical Ventilation at Home	582
Goals of Home Mechanical Ventilation (HMV)	582
Indications and Contraindications	583
Patient Selection	586
Equipment Selection	587
Mechanical Ventilation in Mass Casualty Incidents	589
Causes of Mass Casualty	589
Mass Casualty and Mechanical Ventilation	590
Triage Systems for Mass Casualty Incidents	591
Strategic National Stockpile	594
Exclusion Criteria for Mechanical Ventilation	595
Personnel and Planning	596
Mechanical Ventilation in Hyperbaric Condition	596
Rationale for Hyperbaric Oxygenation (HBO)	596
Indications for HBO	597
Endotracheal Tube and Ventilator	597
Tidal Volume Fluctuations	598
Monitoring and Mechanical Ventilation	599
Defibrillation and Cardiac Pacing	599
Mechanical Ventilation in Hypobaric Condition	601
High-Altitude Cerebral and Pulmonary Edema	602
Airplane Cabin Pressure	602
Ventilator Parameter Changes under Hypobaric Conditions	603
Pressure Compensation	604
Traveling with Portable Ventilators	604
Characteristics of Portable Ventilators	605
Traveling in the United States	605

Adjustment of Tidal Volume 606
Portable Oxygen Concentrator 607
Summary 608
Self-Assessment Questions 608
Answers to Self-Assessment Questions 610
References 610
Additional Resources 614

CHAPTER 19: CASE STUDIES

Case 1: COPD 616
Case 2: Status Asthmaticus 620
Case 3: Post-Abdominal Surgery 625
Case 4: Head Injury 628
Case 5: Smoke Inhalation 631
Case 6: Drug Overdose 635
Case 7: Tension Hemopneumothorax 639
Case 8: Chest Trauma 644
Case 9: Acute Respiratory Distress Syndrome 649
Case 10: Myasthenia Gravis 656
Case 11: Guillain-Barré 660
Case 12: Botulism 667
Case 13: Meconium Aspiration/Patent Ductus Arteriosus 672
Case 14: Persistent Pulmonary Hypertension of the Newborn 676
Case 15: Home Care and Disease Management 678
Case 16: End-of-Life Sedation on Mechanical Ventilation 685

Appendix 1: Respiratory Care Calculations 689
A. *Arterial Oxygen Tension to Inspired Oxygen Concentration (PaO_2/F_IO_2) Index* 689
B. *Cardiac Output (CO): Fick's Estimated Method* 689
C. *Cerebral Perfusion Pressure* 690
D. *Compliance: Dynamic (C_{DYN})* 691
E. *Compliance: Static (C_{ST})* 691
F. *Corrected Tidal Volume (V_T)* 692
G. *Deadspace to Tidal Volume Ratio (V_D/V_T)* 692
H. *I:E Ratio* 693
I. *Mean Airway Pressure (mPaw)* 694
J. *Minute Ventilation: Expired and Alveolar* 695
K. *Oxygen Content: Arterial (CaO_2)* 695
L. *Oxygen Index (OI)* 696
M. *Shunt Equation (Q_{SP}/Q_T): Classic Physiologic* 696
N. *Shunt Equation (Q_{SP}/Q_T): Estimated* 697
O. *Vascular Resistance: Pulmonary* 698

P. Vascular Resistance: Systemic 699
Q. Ventilator Rate Needed for a Desired $PaCO_2$ 699
R. Weaning Index: Rapid Shallow Breathing 700

Appendix 2: Normal Electrolyte Concentrations in Plasma 701
Appendix 3: Oxygen Transport Normal Ranges 702
Appendix 4: Hemodynamic Normal Ranges 703
Appendix 5: Glasgow Coma Score 705
Appendix 6: Apache II Severity of Disease Classification System 706

Glossary 708
Index 719

Preface

Mechanical ventilation has been an integral part of critical care medicine. In its earlier years, ventilators were mainly used in the intensive care units and occasionally in the emergency departments for patient stabilization and intrahospital transport. In recent years, ventilators are used frequently in interhospital and intercontinental transport of critically ill patients. They are also used in mass casualty events, in both hyperbaric and hypobaric environments. Technology has evolved to a point where patients can manage the basic functions of their ventilators at home and even on a commercial aircraft.

Due to the inherited limitations of printed media, it would be impossible to provide adequate coverage on all topics, theories, procedures, and equipment related to mechanical ventilation. As a tradeoff, the primary focus of this mechanical ventilation textbook is to provide a basic but thorough presentation of those relevant topics that are pertinent to everyday clinical practice. Users of information technology and the Internet would agree that "more is not better." This book attempts to strike a balance between an adequate coverage in theory and a spectrum of needed clinical knowledge. The learners should find this book useful to develop a solid foundation in the theories of mechanical ventilation. With additional clinical experience, the learners should be able to integrate and apply the theories of mechanical ventilation in a clinical setting for better patient care.

In the fourth edition of *Clinical Application of Mechanical Ventilation*, new information and numerous references have been added. In some cases, older references are retained because their unique contribution has not been duplicated or cannot be found elsewhere. These classic references also allow learners and researchers to follow the path of progression in the knowledge and techniques of mechanical ventilation.

Overview of Textbook

In this fourth edition, the key terms are boldfaced within the text and the definitions are placed in the margin for quick reference. Essential information is also highlighted in the margin for quick reference. Learning objectives can be found in the beginning of Chapters 1 through 18.

Chapter 1 of the fourth edition reviews the normal pulmonary mechanics and the abnormal physiologic conditions leading to ventilatory failure. Chapter 2 provides a review of the effects of positive pressure ventilation on the major body systems and organs. Chapter 3 covers the components, terminology, and classification of mechanical ventilators. Chapter 4 describes up-to-date operating modes of mechanical ventilation. Chapter 5 reviews some special airways that are used to facilitate ventilation and oxygenation. Chapter 6 covers the application, management, and complications of endotracheal and tracheostomy tubes. Chapter 7 presents the clinical application of noninvasive positive pressure ventilation and the associated interfaces. Chapter 8 offers the common procedures for the initiation of mechanical ventilation. The indications, contraindications, initial ventilator settings, and alarm settings relating to mechanical ventilation are also discussed. Chapter 9 outlines the essential methods of patient monitoring to include imaging, fluid balance, blood gases, pulse oximetry, capnography, transcutaneous blood gases, and cerebral perfusion pressure. Chapter 10 covers the basics of invasive, less invasive and noninvasive hemodynamic monitoring. Chapter 11 gives a detailed discussion on ventilator waveform analysis and its applications. Chapter 12 presents the strategies to improve ventilation and oxygenation during mechanical ventilation. It also describes the basic strategies to manage ventilator alarms and abnormal physiologic conditions during mechanical ventilation. Chapter 13 reviews the basic pharmacotherapy for mechanical ventilation. The drugs discussed in this chapter include bronchodilators, neuromuscular blockers, central nervous agents, and other agents to facilitate patient comfort and patient-ventilator synchrony. Chapter 14 includes special procedures associated with mechanical ventilation—chest tube and drainage system, fiberoptic bronchoscopy, and transport of mechanically ventilated patients. Chapter 15 reviews some critical care issues in mechanical ventilation—acute lung injury, acute respiratory distress syndrome, ventilator-associated pneumonia, hypoxic-ischemic encephalopathy, and traumatic brain injury. Chapter 16 includes the criteria, procedure, and protocol for weaning from mechanical ventilation. Weaning failure and terminal weaning are also discussed. Chapter 17 covers a wide spectrum of neonatal mechanical ventilation to include high-frequency oscillatory ventilation and extracorporeal membrane oxygenation. In Chapter 18, mechanical ventilation in nontraditional settings is discussed. These settings include the use of a ventilator at home, in a mass casualty situation, in hyperbaric and hypobaric environments, as well as traveling with a mechanical ventilator on commercial aircraft. Chapter 19 has sixteen case studies related to mechanical ventilation.

New to This Edition

The fourth edition of *Clinical Application of Mechanical Ventilation* has two new chapters. Chapter 15 covers five critical care issues in mechanical ventilation that are commonly encountered by critical care providers. They are acute lung injury, acute respiratory distress syndrome, ventilator-associated pneumonia, hypoxic-ischemic encephalopathy, and traumatic brain injury. A recruitment maneuver to determine optimal PEEP is also included in Chapter 15. In Chapter 18, mechanical ventilation in nontraditional settings is discussed. These settings include the use of a ventilator at home, in a mass casualty situation, in hyperbaric and hypobaric environments, and on commercial aircraft. This new edition also provides much updated information. For example, modes of ventilation are updated in Chapter 4 to reflect current practice. Special visualization devices for intubation are added in Chapter 6. Less invasive and noninvasive hemodynamic monitoring techniques are added in Chapter 10. Weaning in progress and weaning protocols are updated in Chapter 16. In Chapter 19, a new case study covers the medical and ethical aspects of terminal weaning. The Appendices are updated to provide more useful reference information for the use and management of mechanical ventilation.

Ancillary Package

The complete supplement package for *Clinical Application of Mechanical Ventilation, fourth edition* was developed to achieve two goals:

1. To assist students in the learning and applying the information presented in the test.
2. To assist instructors in planning and implementing their courses in the most efficient manner and provide exceptional resources to enhance their students' experience.

Instructor Companion Website

ISBN 13: 978-1-111-53968-9

Spend less time planning and more time teaching with Delmar Cengage Learning's Instructor Resources to Accompany *Clinical Application of Mechanical Ventilation, fourth edition*. The Instructor Companion Website can be accessed by going to www.cengage.com/login to create a unique user log-in. The password-protected Instructor Resources include the following:

Instructor's Manual

An electronic instructor's manual provides instructors with invaluable tools for preparing for class lectures and examinations. The instructor's manual consists of three sections. The first section is a collection of potential test bank questions for each chapter, followed the second section that houses the answers for quick and easy assessment. The third section of the instructor's manual provides the answers to the workbook questions and exercises.

Computerized Test Bank in ExamView™

An electronic testbank makes and generates tests and quizzes in an instant. With a variety of question types, including short answer, multiple choice, true or false, and matching exercises, creating challenging exams will be no barrier in your classroom. This testbank includes a rich bank of questions that test students on retention and application of what they've learned in the course. Answers are provided for all questions so instructors can focus on teaching, not grading.

Student Workbook

ISBN 13: 978-1-111-53967-2

The Student Workbook to accompany the fourth edition of Clinical Application of Mechanical Ventilation is a powerful learning aid for students and will enhance their comprehension and ability to apply what they have learned. Each workbook chapter follows the core textbook and supplies students with a variety of challenging exercises and quizzes to complete. This Workbook is a great asset to students and instructors alike to support active participation and engage the learning process.

Features of the Fourth Edition

The fourth edition includes many tried and true features that will enhance the learning experience and make this textbook a valuable asset in your education.

The addition of **Learning Objectives** listed at the beginning of each chapter outlines expected outcomes and is a great assessment tool after you've read the chapter. Another new feature is **Additional Resources,** which lists several assets in various media types that you can use to further your understanding of the chapter topics. Other features that offer guided study are a **Key Terms** list for each chapter and corresponding margin definitions for quick and easy reference. **Margin Notes** can be found throughout the chapters and succinctly present critical information for each chapter. Chapter **tables** and **figures** are improved with a brand new design and a second color to add prominence and draw attention to the information contained therein. Rounding out the important features of the fourth edition are the **Self-Assessment Questions** found at the end of each chapter that challenge you to apply the knowledge you've acquired throughout the chapter. **Answers** to the questions are included in each chapter for quick assessment to identify areas of weakness, and where further study is needed.

As in the past three editions, the goal of the fourth edition of *Clinical Application of Mechanical Ventilation* is to provide the students a textbook they will enjoy reading and using at school and at home. It is also my goal to make this textbook a quick reference source for respiratory care practitioners and other critical care providers.

—David W. Chang

Acknowledgments

I thank my colleagues Hanns Billmayer, Frank Dennison, Paul Eberle, Janelle Gardiner, Luis Gonzalez III, Gary Hamelin, Michell Oki, Frank Rando, Lisa Trujillo, Jonathan Waugh, and Gary White for writing or revising chapters and case studies in the fourth edition of *Clinical Application of Mechanical Ventilation*. My special appreciation goes to Dr. David Hassell for the chest radiographs showing thoracic vascular lines. Their knowledge and experience in different aspects of critical care have made this edition clinically relevant and practical. I also thank other colleagues for their help in many different capacities for the last three editions. Their contribution to the process of teaching and learning is evident throughout the pages of this book.

I would also like to recognize my colleagues who reviewed the contents of this edition for completeness and accuracy. Their help is very much appreciated throughout the development of this manuscript. They provided corrections, suggestions, and useful comments. The fourth edition of *Clinical Application of Mechanical Ventilation* should continue to be a useful textbook for students and a helpful reference source for critical care providers. The reviewers are:

Eileen G Durant, MEd, RRT, MS
Assistant Professor/Director of Clinical Education
Tallahassee Community College
Tallahassee, Florida

Doug Gibson, RRT, RCP
Program Director
Respiratory Care Technology Program,
McLennan Community College
Waco, Texas

Elgloria A. Harrison MS, RRT, NPS, AE-C
Associate Professor, Chair, Department of Nursing, the Health Professions, and the Institute of Gerontology
University of the District of Columbia
Washington, D.C.

Todd Klopfenstein, MS, RRT
Program Director
Alegent Health/Midland University,
School of Respiratory Therapy
Omaha, Nebraska

Daniel Knue, MM, RRT-NPS
Director Allied Health and Respiratory Care
Muskegon Community College
Muskegon, Michigan

Publishing a textbook and its accompanying workbook and instructor's manual is a team effort. I thank my team of professionals and individuals for making this task a rewarding experience. My team members are: Associate Acquisition Editor Christina Gifford, Associate Product Manager Meghan Orvis, and Senior Content Project Manager Kara A. DiCaterino.

Contributors to the Fourth Edition

Frank Dennison, MEd, RRT, RPFT
Formerly of Medical College of Georgia
Augusta, Georgia

Paul G. Eberle, PhD, RRT
Weber State University
Ogden, Utah

Janelle Gardiner, MS, RRT, AE-C
Weber State University
Ogden, Utah

Luis S. Gonzalez III, PharmD, BCPS
Memorial Medical Center
Johnstown, Pennsylvania

Gary Hamelin, MS, RRT
South Maine Community College
South Portland, Maine

Michell Oki, MPAcc, RRT
Weber State University
Ogden, Utah

Frank Rando, PA, RCP, CRT, EMT-P
Health Systems Preparedness & Homeland Security Advisor
Tucson, Arizona

Lisa Trujillo, MS, RRT
Weber State University
Ogden, Utah

Jonathan B. Waugh, PhD, RRT, RPFT
University of Alabama at Birmingham
Birmingham, Alabama

Gary White, MEd, RRT, CPFT
Spokane Community College
Spokane, Washington

Chapter 1

Principles of Mechanical Ventilation

David W. Chang

Outline

Introduction

Airway Resistance

- *Factors Affecting Airway Resistance*
- *Airway Resistance and the Work of Breathing (ΔP)*
- *Effects on Ventilation and Oxygenation*
- *Airflow Resistance*

Lung Compliance

- *Compliance Measurement*
- *Static and Dynamic Compliance*
- *Compliance and the Work of Breathing*
- *Effects on Ventilation and Oxygenation*

Deadspace Ventilation

- *Anatomic Deadspace*
- *Alveolar Deadspace*
- *Physiologic Deadspace*

Ventilatory Failure

- *Hypoventilation*
- *Ventilation/Perfusion (V/Q) Mismatch*
- *Intrapulmonary Shunting*
- *Diffusion Defect*

Oxygenation Failure

- *Hypoxemia and Hypoxia*

Clinical Conditions Leading to Mechanical Ventilation

- *Depressed Respiratory Drive*
- *Excessive Ventilatory Workload*
- *Failure of Ventilatory Pump*

Summary

Self-Assessment Questions

Answers to Self-Assessment Questions

References

Additional Resources

Key Terms

airway resistance
alveolar deadspace
alveolar volume
anatomic deadspace
deadspace ventilation
diffusion defect

hypoventilation
hypoxic hypoxia
intrapulmonary shunting
lung compliance
oxygenation failure
peak inspiratory pressure
physiologic deadspace
plateau pressure
refractory hypoxemia
ventilatory failure
V/Q mismatch

Learning Objectives

After studying this chapter and completing the review questions, the learner should be able to:

- Use required variables and calculate airway resistance, compliance, and deadspace ventilation.
- Describe the relationship among the three variables in airway resistance, compliance, and deadspace ventilation.
- Describe the clinical application of static and dynamic compliance.
- Explain the changes in airway resistance, lung compliance, and deadspace ventilation that contribute to the increased work of breathing and ventilatory failure.
- Describe the process of four clinical conditions that lead to ventilatory failure.
- Identify the presence of hypoxemia and signs of hypoxia.
- Describe three primary clinical conditions that lead to mechanical ventilation.

INTRODUCTION

Mechanical ventilation is a useful modality for patients who are unable to sustain the level of ventilation necessary to maintain the gas exchange functions (oxygenation and carbon dioxide elimination). Indications for mechanical ventilation vary greatly among patients. Mechanical ventilation may be indicated in conditions due to physiologic changes (e.g., deterioration of lung parenchyma), disease states (e.g., respiratory distress syndrome), medical/surgical procedures (e.g., postanesthesia recovery), and many other causes (e.g., head trauma, drug overdose) leading to ventilatory failure or oxygenation failure.

Use of mechanical ventilation also varies greatly from short term to long term and from acute care in the hospital to extended care at home. One of the most frequent uses of mechanical ventilation is for the management of postoperative patients recovering from anesthesia and medications. Other indications for mechanical ventilation in adults include apnea and impending respiratory arrest, acute exacerbation of COPD, acute severe asthma, neuromuscular disease, acute hypoxemic respiratory failure, heart failure and cardiogenic shock, acute brain injury, and flail chest (Pierson, 2002).

Regardless of the diagnosis or disease state, patients who require mechanical ventilation generally have developed ventilatory failure, oxygenation failure, or both. Specifically, when a patient fails to ventilate or oxygenate adequately, the problem may be caused by one of six major pathophysiological factors: (1) increased airway resistance, (2) changes in lung compliance, (3) hypoventilation, (4) V/Q mismatch, (5) intrapulmonary shunting, or (6) diffusion defect.

AIRWAY RESISTANCE

airway resistance: The degree of airflow obstruction in the airways.

Airway resistance is defined as airflow obstruction in the airways. In mechanical ventilation, the degree of airway resistance is primarily affected by the length, size, and patency of the airway, endotracheal tube, and ventilator circuit.

Factors Affecting Airway Resistance

Airway resistance causes obstruction of airflow in the airways. It is increased when the patency or diameter of the airways is reduced. Obstruction of airflow may be caused by: (1) changes inside the airway (e.g., retained secretions), (2) changes in the wall of the airway (e.g., neoplasm of the bronchial muscle structure), or (3) changes outside the airway (e.g., tumors surrounding and compressing the airway) (West, 2007). When one of these conditions occurs, the radius of the airway decreases and airway resistance increases. According to the simplified form of Poiseuille's Law, the driving pressure (ΔP) to maintain the same airflow ($\dot{V}$) must increase by a factor of 16-fold when the radius (r) of the airway is reduced by only half of its original size.

$$\text{Simplified form of Poiseuille's Law: } \Delta P = \frac{\dot{V}}{r^4}$$

✔ Based on Poiseuille's Law, the work of breathing increases by a factor of 16-fold when the radius (r) of the airway is reduced by half its original size.

One of the most common causes of increased airway resistance is chronic obstructive pulmonary disease (COPD). This type of lung disease includes emphysema, chronic bronchitis, chronic asthma, and bronchiectasis. Mechanical conditions that may increase airway resistance include postintubation obstruction and foreign body aspiration. Infectious processes include laryngotracheobronchitis (croup), epiglottitis, and bronchiolitis. Table 1-1 lists three categories of clinical conditions that increase airway resistance.

✔ Airway resistance varies directly with the length and inversely with the diameter of the airway or ET tube.

Normal airway resistance in healthy adults is between 0.5 and 2.5 cm H_2O/L/sec (Wilkins, 2009). It is higher in intubated patients due to the smaller diameter of the endotracheal (ET) tube. Airway resistance varies directly with the length and inversely with the diameter of the airway or ET tube. In the clinical setting, the ET tube may be shortened for ease of airway management, reduction of mechanical deadspace, and reduction of airway resistance. However, the major contributor to increased airway resistance is the internal diameter of the ET tube. Therefore, during intubation, the largest appropriate size ET tube must be used so that the airway resistance contributed by the ET tube may be minimized. Once the ET tube is in place,

TABLE 1-1 Clinical Conditions That Increase Airway Resistance

Type	Clinical Conditions
COPD	Emphysema Chronic bronchitis Asthma Bronchiectasis
Mechanical obstruction	Postintubation obstruction Foreign body aspiration Endotracheal tube Condensation in ventilator circuit
Infection	Laryngotracheobronchitis (croup) Epiglottitis Bronchiolitis

its patency must be maintained, as secretions inside the ET tube greatly increase airway resistance.

Besides the ET tube, the ventilator circuit may also impose mechanical resistance to airflow and contribute to total airway resistance. This is particularly important when there is a significant amount of water in the ventilator circuit due to condensation. Chapter 4 describes the use of pressure support ventilation (PSV) to compensate for the effects of airflow resistance and to augment spontaneous tidal volume during mechanical ventilation.

Airway Resistance and the Work of Breathing (ΔP)

Airway resistance is calculated by $\frac{\text{Pressure Change}}{\text{Flow}}$

$$\text{Raw} = \frac{\Delta P}{\dot{V}}$$

$$\text{Raw} = \text{airway resistance}$$

$$\Delta P = \text{pressure change (Peak Inspiratory Pressure} - \text{Plateau Pressure)}$$

$$\dot{V} = \text{Flow}$$

✔ ↑ Airway resistance = ↑ Work of breathing.

The pressure change (ΔP) in the equation reflects the work of breathing imposed on the patient. Since airway resistance is directly related to pressure change (the work of breathing), an increase in airway resistance means the patient must exert more energy for ventilation. In a clinical setting, relief of airflow obstruction is an effective way to reduce the work of breathing (Blanch et al., 2005; Myers, 2006).

If pressure change (work of breathing) in the equation above is held constant, an increase in airway resistance will cause a decrease in flow and subsequently a decrease

hypoventilation: Inadequacy of ventilation to remove CO_2. The arterial PCO_2 is elevated in conditions of hypoventilation.

in minute ventilation. This is because airway resistance and flow in the equation are *inversely* related. In a clinical setting, **hypoventilation** may result if the patient is unable to overcome the airway resistance by increasing the work of breathing.

As a result of chronic air trapping, patients with chronic airway obstruction may develop highly compliant lung parenchyma. These patients use a breathing pattern that is deeper but slower. On the other hand, patients with restrictive lung disease (low compliance) breathe more shallowly but faster, since airflow resistance is not the primary disturbance in these patients.

ventilatory failure: Failure of the respiratory system to remove CO_2 from the body resulting in an abnormally high $PaCO_2$.

oxygenation failure: Failure of the heart and lungs to provide adequate oxygen for metabolic needs.

Effects on Ventilation and Oxygenation

The work of breathing imposed on a patient is increased when airway resistance is high. This creates a detrimental effect on the patient's ventilatory and oxygenation status. If an abnormally high airway resistance is sustained over a long time, fatigue of the respiratory muscles may occur, leading to ventilatory and oxygenation failure (Rochester, 1993). **Ventilatory failure** occurs when the patient's minute ventilation cannot keep up with CO_2 production. **Oxygenation failure** usually follows when the cardiopulmonary system cannot provide adequate oxygen needed for metabolism.

✔ An increased bowing of the P-V loop suggests an overall increase in airflow resistance.

✔ Excessive inspiratory flow → bowing of inspiratory limb. (A_1 to A_2)

Airflow Resistance

The airflow resistance of a patient-ventilator system may be monitored using the pressure-volume (P-V) loop display on a ventilator waveform display (Waugh et al., 2007). An increased bowing of the P-V loop suggests an overall increase in airflow resistance (Figure 1-1). The increase in airflow resistance may be caused by excessive inspiratory flow or increased expiratory flow resistance.

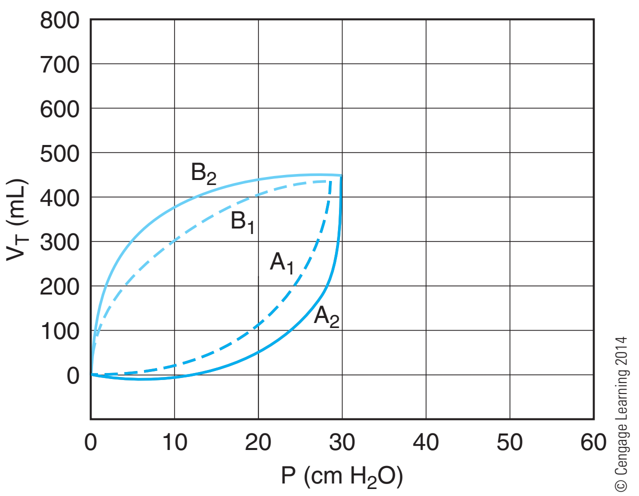

FIGURE 1-1 Increased bowing (from dotted to solid lines) of the pressure–volume loop suggests an increase in airflow resistance. Bowing of inspiratory limb (from A_1 to A_2) may be caused by excessive inspiratory flow. Bowing of the expiratory limb (from B_1 to B_2) may be caused by an increase in expiratory flow resistance such as bronchospasm.

Increased expiratory flow resistance → bowing of expiratory limb. (B_1 to B_2)

When the inspiratory flow exceeds a patient's tidal volume and inspiratory time requirement, bowing of the inspiratory limb may result (line A_2). In situations where the expiratory airflow resistance is increased (e.g., bronchospasm), bowing of the expiratory limb (line B_2) may occur.

LUNG COMPLIANCE

lung compliance: The degree of lung expansion per unit pressure change.

Lung compliance is volume change (lung expansion) per unit pressure change (work of breathing), and it is calculated by $C = \Delta V/\Delta P$, where C = compliance, ΔV = volume change, and ΔP = pressure change. Most ventilators can measure and show the static and dynamic compliance values on the data or graphic display. A method to measure and calculate static and dynamic compliance is outlined in Table 1-2.

refractory hypoxemia: A persistent low level of oxygen in blood that is not responsive to medium to high concentration of inspired oxygen. It is usually caused by intrapulmonary shunting.

plateau pressure: The pressure needed to maintain lung inflation in the absence of airflow.

peak inspiratory pressure: The pressure used to deliver the tidal volume by overcoming nonelastic (airways) and elastic (lung parenchyma) resistance.

Compliance Measurement

Abnormally low or high lung compliance impairs the patient's ability to maintain efficient gas exchange. Low compliance typically makes lung expansion difficult. High compliance induces incomplete exhalation, air trapping, and reduced CO_2 elimination. These abnormalities are often contributing factors to the need for mechanical ventilation.

Low Compliance. Low compliance (high elastance) means that the volume change is small per unit pressure change. Under this condition, the lungs are *stiff* or *noncompliant*. The work of breathing is increased when the compliance is low. In many clinical situations (e.g., acute respiratory distress syndrome or ARDS), low lung compliance is associated with **refractory hypoxemia**.

TABLE 1-2 Method to Measure Static and Dynamic Compliance

(1) Obtain corrected expired tidal volume.
(2) Obtain **plateau pressure** by applying inspiratory hold or occluding the exhalation port at end-inspiration.
(3) Obtain **peak inspiratory pressure.**
(4) Obtain positive end-expiratory pressure (PEEP) level, if any.

$$\text{Static Compliance} = \frac{\text{Corrected Tidal Volume}}{(\text{Plateau Pressure} - \text{PEEP})}$$

$$\text{Dynamic Compliance} = \frac{\text{Corrected Tidal Volume}}{(\text{Peak Inspiratory Pressure} - \text{PEEP})}$$

TABLE 1-3 Clinical Conditions That Decrease the Compliance

Type of Compliance	Clinical Conditions
Static compliance	ARDS Atelectasis Tension pneumothorax Obesity Retained secretions
Dynamic compliance	Bronchospasm Kinking of ET tube Airway obstruction

© Cengage Learning 2014

↓ Lung compliance = ↑ Work of breathing.

Low compliance measurements are usually related to conditions that reduce the patient's functional residual capacity. Patients with noncompliant lungs often have a restrictive lung defect, low lung volumes, and low minute ventilation. This condition may be compensated for by an increased frequency. Table 1-3 shows some examples that lead to a decreased compliance measurement.

In extreme high compliance situations, exhalation is often incomplete due to reduced elastic recoil of the lungs.

High Compliance. High compliance means that the volume change is large per unit pressure change. In extreme high compliance situations, exhalation is often incomplete due to lack of elastic recoil by the lungs. Emphysema is an example of high compliance where the gas exchange process is impaired. This condition is due to chronic air trapping, destruction of lung tissues, and enlargement of terminal and respiratory bronchioles.

High compliance measurements are usually related to conditions that increase the patient's functional residual capacity and total lung capacity. Patients with extremely compliant lungs often develop airflow obstruction, incomplete exhalation, air trapping, and poor gas exchange.

Static and Dynamic Compliance

Assessment of compliance can be divided into static compliance and dynamic compliance measurements. The relationship and clinical significance of these measurements are discussed in the following sections.

Static compliance reflects the elastic properties (elastic resistance) of the lung and chest wall.

Static Compliance. Static compliance is calculated by dividing the volume by the pressure (i.e., plateau pressure) measured when the flow is momentarily stopped. When airflow is absent, airway resistance becomes a non-factor. Static compliance reflects the elastic resistance of the lung and chest wall.

Dynamic compliance reflects the airway resistance (nonelastic resistance) and the elastic properties of the lung and chest wall (elastic resistance).

Dynamic Compliance. Dynamic compliance is calculated by dividing the volume by the pressure (i.e., peak inspiratory pressure) measured when airflow is present. Since airflow is present, airway resistance becomes a factor in the measurement of dynamic compliance. Dynamic compliance therefore reflects the condition of airway

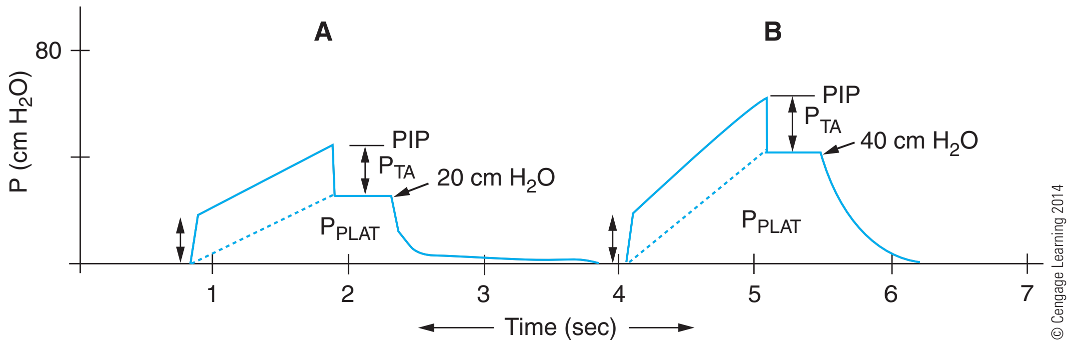

FIGURE 1-2 In conditions where the lung compliance is decreased (e.g., atelectasis), the plateau pressure (P_{PLAT}) and peak inspiratory pressure (PIP) are both increased (from A to B).

resistance (nonelastic resistance) as well as the elastic properties of the lung and chest wall (elastic resistance).

> ✔ Conditions causing changes in plateau pressure and static compliance invoke similar changes in peak inspiratory pressure and dynamic compliance.

Plateau and Peak Inspiratory Pressure. In general, conditions causing changes in plateau pressure and static compliance invoke similar changes in peak inspiratory pressure and dynamic compliance. For example, atelectasis causes an increase of plateau and peak inspiratory pressures (Figure 1-2, A to B). Since the plateau and peak inspiratory pressures are increased, the calculated static and dynamic compliance measurements are decreased. When atelectasis is resolved, the plateau and peak inspiratory pressures return to normal (Figure 1-2, B to A).

> ✔ When the airflow resistance is increased (e.g., bronchospasm), the peak inspiratory pressure is increased while the plateau pressure stays unchanged.

In conditions where the airflow resistance is increased (e.g., bronchospasm), the peak inspiratory pressure is increased while the plateau pressure stays unchanged (Figure 1-3, A to B). Since the peak inspiratory pressure is increased, the dynamic compliance is decreased. The static compliance stays the same because there is no change in the plateau pressure. When bronchospasm is resolved, the peak inspiratory pressure and dynamic compliance measurements return to their previous states. (Figure 1-3, B to A).

Pressure-Volume Loop. Since compliance is determined by $\Delta V/\Delta P$, the P-V loop is essentially a "compliance loop," and it provides useful information on the characteristics of a patient's compliance. Figure 1-4 shows a P-V loop during a mandatory

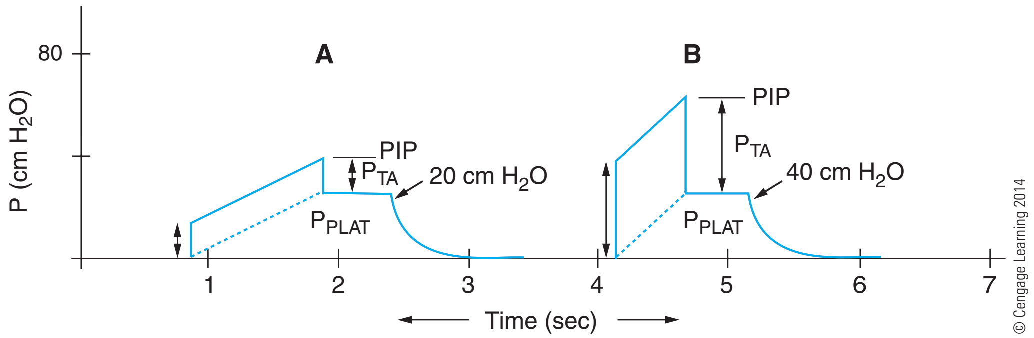

FIGURE 1-3 In conditions where the airflow resistance is increased (e.g., bronchospasm), the peak inspiratory pressure (PIP) is increased while the plateau pressure (P_{PLAT}) stays unchanged (from A to B).

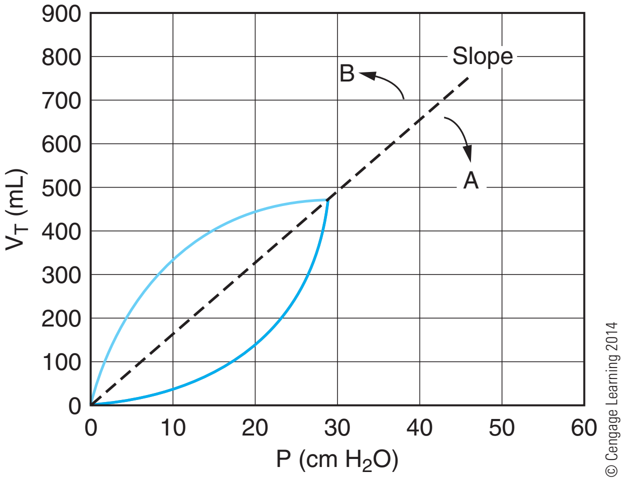

FIGURE 1-4 Shifting of the P-V slope toward the pressure axis (A) indicates a decrease in compliance. Shifting of the P-V slope toward the volume axis (B) indicates an increase in compliance.

> ✔ A shift of the slope toward the pressure axis indicates a decrease in compliance.

> ✔ A shift of the slope toward the volume axis indicates an increase in compliance.

breath. A slope is drawn from the beginning point dividing the inspiratory limb and the expiratory limb. A shift of the slope toward the pressure axis indicates a decrease in compliance. A shift of the slope toward the volume axis indicates an increase in compliance (Waugh et al., 2007).

In another P-V loop (Figure 1-5), a shift of the slope and the entire P-V loop toward the pressure axis shows an increase in pressure (↑ ΔP) required to deliver the same volume (ΔV). This condition shows a decrease in compliance (↓C) (Waugh et al., 2007).

Compliance measurements should be made so that a trend can be established. Interpretation is of little value with a single compliance measurement. It is also essential not to compare static compliance with dynamic compliance measurements as this can cause erroneous and meaningless interpretations.

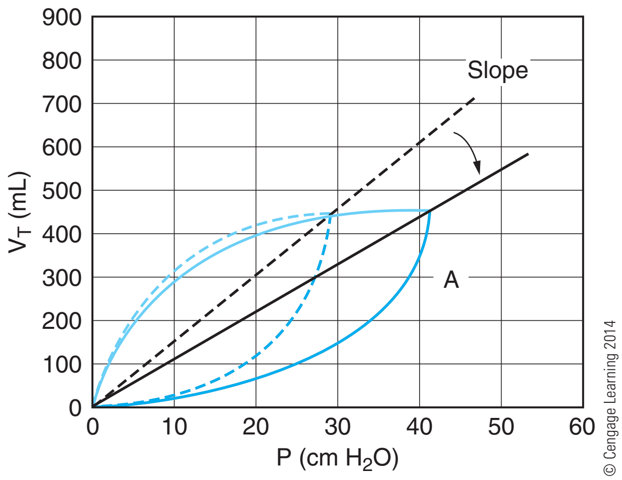

FIGURE 1-5 Shifting of the P-V slope and loop toward the pressure axis shows a higher pressure is required to deliver the same volume (decrease in compliance).