Rumen Health Compendium

Second Edition

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Kendall Hunt
publishing company

Cover images (top to bottom): (left to right): *Prevotella ruminicola*, protozoa, *Lachnospira multipara*, and *Succinimonas amylolytica* by T. J. Hackmann (UC-Davis); *Entodinium* protozoan by S. A. Carlson and M. A. Rasmussen (USDA-ARS); and licensed photos of reticulum and feedlot cattle by Shutterstock.com.

Published in the United States of America

ISBN 979-8-3851-6542-1
Second Edition (January 2025)
First Edition, Second Printing (July 2021)
First Edition (December 2020)

Kendall Hunt
publishing company

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Dubuque, IA 52004-1840

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Foreword

Dear Reader,

The Rumen Health Compendium publication, now in its second edition, aims to outline the main metabolic disorders related to beef and dairy cattle rumen health, making diagnosis easier and supporting best practices and prevention. The format of this publication reflects the importance of this information for veterinarians, nutritionists and managers involved in the daily operations of feeding animals so that they benefit most from the contents.

The second edition contains valuable content which has been expanded and refined to reflect recent research and new information regarding ruminant health and nutrition. Additionally, new authors are featured, as well as several chapters covering information not originally discussed in the first edition.

We would like to give special thanks to the scientists involved in this project. Their contributions, knowledge and experience in this field supported the development of this updated book which we hope will be used as a valuable reference for years to come.

Our special thanks to Dr. Luis O. Tedeschi, Professor of Animal Nutrition, Texas A&M University and Dr. T.G. Nagaraja, University Distinguished Professor of Microbiology, Kansas State University, for their commitment and contributions, as well as the many hours spent selecting, reviewing and refining the contents of this updated compendium.

We are committed to continued investment in additional research to help support animal health and performance. Our mission remains to provide safe and effective solutions for our customers' unique challenges. Our purpose is to optimize animal health and nutrition for better lives and a more sustainable world.

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Teaneck, NJ

October 2024

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Preface to the Second Edition

Welcome to the Second Edition of the Rumen Health Compendium. The interval since the release of our First Edition has witnessed profound growth in our comprehension of rumen health and its pivotal role in ruminant production. This journey from the inception to the current iteration of this compendium has been characterized by significant research advancements, technological leaps, and an enriched understanding of the symbiotic relationship between ruminants and their microbial cohorts.

Ruminants remain unparalleled biomachines, adept at converting human-inedible organic material into valuable, high-quality animal products. Central to this process is the rumen, a complex ecosystem where symbiotic microorganisms orchestrate the breakdown of fibrous plant material into nutrients that sustain ruminant health and productivity. The longstanding evolution of this symbiosis over millions of years underscores its fundamental importance in the ecological and agricultural landscape.

In this Second Edition, we further explore the contemporary issues in ruminant rearing, with an intensified focus on optimizing rumen health through nutritional strategies. We build upon the foundational knowledge introduced in the First Edition, venturing deeper into the anatomy, physiology, and microbiology of the rumen. We also confront emerging challenges and opportunities in ruminant management, emphasizing the significance of proper ruminant management in reducing the environmental impact of ruminants, particularly concerning global warming. The Second Edition has 26 Chapters, 149 illustrations, and 1,717 references.

Part 1: Fundamentals of the gastrointestinal tract broadens the discussion from the anatomy and physiology of the rumen (**Chapter 1**) to encompass the entire gastrointestinal tract (**Chapter 2**), offering a holistic view of the digestive system. The microbial habitat is dissected into discussions on microbiology (**Chapter 3**) and fermentation processes (**Chapter 4**), providing a thorough understanding of the microbial dynamics that drive rumen functionality.

Part 2: Rumen and host health introduces innovative dietary interventions aimed at modulating rumen function and examines the pathology of ruminal dysfunction. We introduce novel insights on rumen modifiers (**Chapters 5 and 6**) and provide an in-depth exploration of the rumen epithelium (**Chapter 7**). The impact of subacute and acute ruminal acidosis (SAARA) on beef (**Chapter 8**) and dairy (**Chapter 9**) rumen health, including microbiome composition changes due to SAARA (**Chapter 10**), is thoroughly discussed. The following chapters address common digestive and metabolic disorders that compromise rumen function, with **Chapter 11** focusing on liver abscess management and **Chapter 12** on bloat and its microbiome interactions (**Chapter 13**). **Chapter 14** highlights the unique challenges of small ruminants, exploring their peculiarities, while **Chapters 15 and 16** look at leaky gut syndrome and hindgut health, respectively, providing comprehensive management strategies. **Chapter 17** investigates the connections and implications between rumen health and lung health, emphasizing the interconnectedness of physiological systems.

Part 3: Toxicity provides a detailed account of plant toxicoses (**Chapter 18**), microbial toxicoses (**Chapter 19**), and urea toxicity (**Chapter 20**), underlining the cause-and-effect relationships between toxic substances and rumen health.

Part 4: Diagnosis of ruminal dysfunctions offers practical guidance on diagnosing rumen disorders, with chapters dedicated to ruminal fluid analysis (**Chapter 21**) and fecal examination (**Chapter 22**), facilitating the assessment and remediation of digestive disorders.

Part 5: Environment and food safety has new additions, addressing the intersection of rumen health with broader environmental issues such as climate stress (**Chapter 23**), methane emissions (**Chapter 24**), food safety (**Chapter 25**), and antimicrobial resistance (**Chapter 26**). This section underscores the critical role of the rumen in navigating the sustainability and ethical challenges of ruminant production; understanding the role of the rumen in mediating these challenges becomes increasingly critical.

Throughout this compendium, we have endeavored to assemble contributions from leading experts across disciplines, ensuring a multidimensional perspective on rumen health and management. Whether you are a seasoned professional or a newcomer to the field, we hope that this compendium will serve as a valuable resource in your quest for knowledge and innovation.

In closing, we extend our gratitude to the contributors, reviewers, and readers whose collective efforts have shaped this compendium into a beacon of knowledge and insight. May the insights contained within these pages inspire novel discoveries and pave the way toward a healthier, more sustainable future for ruminant production.

We highly value your feedback and invite suggestions and comments to enhance future editions of the Rumen Health Compendium. Your insights are crucial to our continued improvement and pursuit of excellence in ruminant health research and practice.

Enjoy your reading journey through the intricate world of rumen health, bolstered by the insights and innovations presented in this Second Edition.

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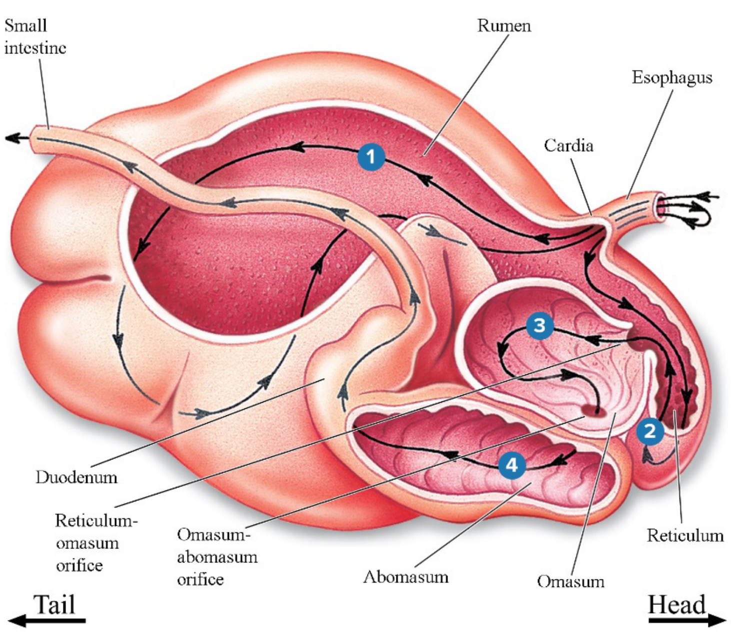
December 2024

Preface to the First Edition

Ruminants are formidable biomachines that are capable of transforming human-inedible organic material, *i.e.*, fibrous plant parts, into human-edible, high-quality animal products (*e.g.*, meat and milk) as a result of a remarkable symbiotic relationship with microbes that co-exist in the reticulorumen. A complex microbiota composed of anaerobic bacteria, fungi, and protozoa resides in the reticulorumen. The rumen microbiota are responsible for the fermentation of complex, polymerized organic material that yields readily available, absorbable products (*e.g.*, acetate, propionate, butyrate), microbial mass, and less polymerized nutrients (*e.g.*, peptides and oligosaccharides), which can be enzymatically digested and absorbed post-ruminally, and further metabolized by the ruminant animal. This cooperative arrangement between ruminants and their reticulorumen microbes is the result of more than 40 million years of evolution and adaptation to diverse ecozones in the four corners of the world. Humans have benefited from ruminants in many ways. Ruminants provide not only high-quality food to humans, ameliorating global hunger, but also draft for crop production and irrigation, transportation, renewable energy, wealth, clothing, and serves for pharmaceutical and biomedical purposes. Ruminants hold enormous importance for the progression of humankind. Therefore, learning how to nurture and care for them is essential not only for their welfare but also to develop sustainable ruminant production under complex grassland-ecosystems.

This book examines contemporary issues related to the rearing of ruminants, especially beef and dairy cattle, focused on maintaining a healthy, functional rumen mainly through nutritional interventions. We invited renowned authorities in the fields of nutrition, microbiology, behavior, veterinary, zoology, and physiology to cover diverse aspects of rumen health and dysfunction. In **Part 1**, we covered the fundaments of the rumen, including anatomy, physiology, rumen development and adaptation, ruminal microbiome, and ruminal contents. In **Part 2**, we delved into the strategic manipulation of the rumen through feeding modifiers, pathology of the rumen wall/epithelium, subacute acidosis, liver abscess due to feeding, bloat, and the poisoning of ruminants due to feeding. **Part 3** emphasized ways to diagnose problems in the reticulorumen through its content's physicochemical characteristics and the visual appraisal of feces. Finally, **Part 4** highlighted common gut foodborne pathogens and a contemporary issue about antimicrobial resistance.



An overview of digesta path (black line with arrows) in the right lateral of cattle's four-chambered stomach: 1 is the rumen, 2 is the reticulum, 3 is the omasum, and 4 is the abomasum. The rumination or "chewing the cud" is represented by the arrows leaving the rumen through the esophagus and looping back. It is reprinted and adapted by permission from McGraw-Hill Education by Johnson © (2018).[760]

As illustrated in the figure in the left, the rumen is by far the largest compartment in the four-chambered stomach of ruminants, and it is located in the caudal section of the four-chambered stomach. The reticulum is the smallest, most cranial section of the four-chambered stomach (**Chapter 1**). The reticulorumen of a mature dairy cow can hold about 200 L. The rumen is lined with papillae that resembles a "shag carpeting" and the reticulum is covered with papillae that resembles a honeycomb structure (**Chapter 2**). The main objective of the reticulorumen papilla is to increase the epithelial surface area to absorb short-chain fatty acids (*e.g.*, acetate, propionate, and butyrate), minerals, and some electrolytes (**Chapter 3**). The reticulum and the rumen are commonly known as the reticulorumen compartment, or collectively known as the rumen. The inclusion of modifiers in diets to enhance animal welfare and health, productivity, and sustainability has been an essential route for administering approved products to livestock intended for food production, but the judicious use of rumen modifiers should be the top priority of nutritionists (**Chapter 4**). Under daily working conditions, it is common to encounter ruminants with health issues brought about by disorders during the fermentation and digestion of the diet that can evolve to cases of ruminitis (**Chapter 5**) and acidosis (**Chapters 6** and **7**), which can lead to liver abscesses (**Chapter 8**). Improperly balanced diets and poor management during feeding and the adaptation phases of ruminants to different dietary regimens can result in some of these disorders, including bloat (**Chapter 9**) or even poisoning (**Chapter 10**) that can lead to poor performance and even death of the animal if not treated on time. Different techniques are available to assist the ruminant caretaker in assessing these disorders, including the analyses of the rumen fluid (**Chapter 11**) or even as simple as a visual appraisal of the feces (**Chapter 12**). Like most food products, food safety is one of the primary concerns for the human population, and many foodborne pathogens can taint ruminant products such as meat and milk (**Chapter 13**). Additionally, making sure that ruminants receive adequate medication when needed without affecting human healthcare practices such as medically important antibiotics (**Chapter 14**) is of utmost importance to foster judicious and sustainable production systems.

The feed is not completely digested in the reticulorumen. The remaining, unfermented digesta escapes the reticulorumen through the reticulum-omasum orifice, a sphincter that separates the reticulum from the omasum. After leaving the reticulorumen, the digesta goes through the omasum, a globular-shaped organ whose primary purpose is for absorbing short-chain fatty acids and water, without the occurrence of further digestive processes. Subsequently, the digesta flows through the abomasum, the fourth compartment of the four-chambered ruminant's stomach, whose function is similar to the glandular stomach of monogastric animals. Other digestive complications exist beyond the rumen, but the most consequential complications often commence in the rumen.

The **Rumen Health Compendium** book was designed to be the first option for knowledge seekers to get acquainted with preliminary information filled with illustrations and applied recommendations related to ruminant production sciences. The book also contains a vast number of references for those in quest of more in-depth knowledge about the topics. Good reading.

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March 2020

Table of Contents

List of Figures

List of Tables

Units of Measurements

Length

Metric	
1 kilometer (km)	1,000 meters (m)
1 meter (m)	1,000 milimeters (mm)
	100 centimeters (cm)
	10 decimeter (dm)
1 centimeter (cm)	10 milimeters (mm)

Imperial	
1 foot (ft)	12 inches (in)
1 mile (mi)	1,760 yard (yd)
	5,280 feet (ft)
1 yard (yd)	3 feet (ft)
	36 inches (in)

Imperial	Metric
1 foot (ft)	30.48 centimeters (cm)
1 inch (in)	2.54 centimeters (cm)
1 league (lea)	4.828 kilometers (km)
1 mile (mi)	1.609 kilometers (km)
1 nautical mile	1.852 kilometers (km)
1 yard (yd)	0.91 meters (m)

Volume

Metric	
1 m^3	1,000 liter (L)
	1,000,000 cm^3

Imperial	
1 gallon (gal US)	4 quart (qt US)
	8 pint (pt US)
	16 cups (US)
1 yd^3	27 ft^3
	46,656 in^3

Imperial	Metric
1 fluid ounce (fl oz US)	29.57 cm^3
1 ft^3	0.028 m^3
	28.32 liters (L)
1 gallon (gal US)	3.785 liters (L)
1 in^3	16.387 cm^3
1 pint (pt US)	0.473 liters (L)
1 quart (qt US)	1.136 liters (L)

Area

Metric	
1 km^2	1,000,000 m^2
	100 hectare (ha)
1 m^2	10,000 cm^2
	100 dm^2

Imperial	
1 acre (ac)	4,840 yd^2
	43,560 ft^2
1 mi^2	640 acre (ac)
1 yd^2	9 ft^2

Imperial	Metric
1 acre (ac)	0.405 hectares (ha)
1 mi^2	2.59 km^2
1 ft^2	0.0929 m^2
	929 cm^2

Mass

Metric	
1 kilogram (kg)	1,000 grams (g)
1 ton (t)	1,000 kilograms (kg)

Imperial	
1 short ton (t US)	2,000 pounds (lb)
1 pound (lb)	16 ounces (oz)

Imperial	Metric
1 ounce (oz)	28.35 grams (g)
1 pound (lb)	0.454 kilograms (kg)
1 short ton (t US)	907.2 kilograms (kg)

Energy

Metric	Imperial
1 calorie (cal IT)	4.1868 joules (J)
1 calorie (cal th)	4.184 joules (J)
1 kilogram-force meter	9.807 joules (J)
1 kilowatt-hour (kW*h)	3,600 kilojoules (kJ)
	3,414.43 Btu (th)

Temperature

Equations	
°F = (9/5)×°C+32	°C = (°F–32) × 5/9
°F = (K–273.15)×9/5+32	K = (°F–32)×5/9+273.15
°C = K–273.15	K = °C+273.15

°C	°F	°C	°F	°C	°F
-26	-14.8	0	32	25	77
-25	-13	1	33.8	26	78.8
-24	-11.2	2	35.6	27	80.6
-23	-9.4	3	37.4	28	82.4
-22	-7.6	4	39.2	29	84.2
-21	-5.8	5	41	30	86
-20	-4	6	42.8	31	87.8
-19	-2.2	7	44.6	32	89.6
-18	-0.4	8	46.4	33	91.4
-17	1.4	9	48.2	34	93.2
-16	3.2	10	50	35	95
-15	5	11	51.8	36	96.8
-14	6.8	12	53.6	37	98.6
-13	8.6	13	55.4	38	100.4
-12	10.4	14	57.2	39	102.2
-11	12.2	15	59	40	104
-9	14	16	60.8	41	105.8
-8	15.8	17	62.6	42	107.6
-7	17.6	18	64.4	43	109.4
-6	19.4	19	66.2	44	111.2
-5	21.2	20	68	45	113
-4	23	21	69.8	46	114.8
-3	24.8	22	71.6	47	116.6
-2	26.6	23	73.4	48	118.4
-1	28.4	24	75.2	49	120.2

Crop weights

1 bushel (bu)	1.244 ft³
1 bu wheat	60 lb
1 bu corn	56 lb
1 bu barley	48 lb
1 bu oats	32 lb

Pressure

Metric	Others
1 kilopascal (kPa)	0.01 bar
1 kPa	0.145 psi
1 kPa	0.009869 atm
1 kPa	1,000 N/m²
1 kPa	10,000 dyne/cm²
1 kPa	101.9716 kg-force/m²
1 kPa	20.8854 lb-force/ft²
1 kPa	0.14504 lb-force/in²
1 kPa	10.1974 cm-water (4°C)

Density

Metric	Imperial
1 kg/L	8.3454 lb/gal US
	998.847 oz/ft³
1 kg/m³	0.0000361273 lb/in³
	0.0624279606 lb/ft³
	0.0005780367 oz/in³
	0.1335264712 oz/gal US

Ratios

Metric	Imperial
1 L/ha	0.1069 gal US/ac
	0.4276 qt US/ac
1 L/m²	3.14143 oz/ft²
1 t/ha	0.44609 t US/ac
1 kg/ha	0.8922 lb/ac
1 kg/m²	0.2048 lb/ft²
1 g/m²	0.003277 oz/ft²
1 m/s	2.23694 miles/h
1 km/h	0.9113 ft/h
	0.6213 miles/h
1 L/t	0.2396 gal US/t US

Online converters:

- https://www.unitconverters.net
- https://www.nist.gov/pml/owm/metric-si/unit-conversion

Abbreviations

Acronym	Description
3-NOP	3-nitrooxypropanol
AA	Amino acids
ADF	Acid detergent fiber
ADG	Average daily gain
AF	Aflatoxin
AHR	Aryl hydrocarbon receptor
AMP	Antimicrobial peptides
AMR	Antimicrobial resistance
APP	Acute phase proteins
ARG	Antimicrobial resistance genes
ASL	Air surface liquid
AST	Antimicrobial susceptibility testing
ATP	Adenosine triphosphate
BAL	Bronchoalveolar lavage
BCAA	Branched-chain amino acids
BCVFA	Branched-chain volatile fatty acids
BEA	Beauvericin
BRD	Bovine respiratory disease
BRSV	Bovine respiratory syncytial virus
BW	Body weight
CAZyme	Carbohydrate-active enzyme
CETI	Current effective temperature index
CFU	Colony forming unit
CGF	Corn gluten feed
CH_4	Methane
CLA	Conjugated linoleic acid
CLSI	Clinical and Laboratory Standards Institute
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CP	Crude protein
CT	Condensed tannins
DAMP	Damage-associated molecular patterns
DAS	Diacetoxyscirpenol
DFM	Direct-fed microbials
DG	Distillers' grain
DM	Dry matter
DMI	Dry matter intake
DNA	Deoxyribonucleic acid
DON	Deoxynivalenol
EA	Ergot alkaloids
ECOFF	Epidemiological cutoff
EFSA	European Food Safety Authority
EGR	Esophageal groove reflex
EN	Enniatins
EO	Essential oils
ESBL	Extended-spectrum beta-lactamases
EU	European Union

Acronym	Description
EUCAST	European Union Committee on Antimicrobial Susceptibility Testing
FAO	Food and Agriculture Organization
FB	Fumonisin
FDA	Food and Drug Administration
FDA/CVM	Food and Drug Administration Center for Veterinary Medicine
FS	Fecal score
FUS	Fusaric acid
G:F	Gain-to-feed ratio
GH	Glycosyl hydrolases
GHG	Greenhouse gas
GIT	Gastrointestinal tract
HAP	Haptoglobin (also, HP)
HFCG	Hydrogenated fat-embedded calcium gluconate
HP	Haptoglobin (also, HAP)
HSF	Heat stress adjustment factor
ICE	Integrative conjugative element
IgA	Immunoglobulin A
IgG	Immunoglobulin G
IPCC	Intergovernmental Panel on Climate Change
ITS	Internal transcribed spacer
kd	Rate of degradation
kp	Rate of passage
LBP	LPS-binding protein
LPCH	Lysophosphatidylcholines
LPS	Lipopolysaccharides
LR	Large ruminants
MAG	Metagenome-assembled-genomes
MALDI-TOF MS	Matrix-associated laser desorption ionization-time of flight mass spectrometry
MAMP	Microbe-associated molecular patterns
MCP	Microbial crude protein
ME	Metabolizable energy
MIC	Minimal inhibitory concentrations
ML	Maximum levels
MON	Moniliformin
MPA	Mycophenolic acid
MSP	Multispecies probiotic
NARMS	National Antimicrobial Resistance Monitoring System
NASEM	National Academies of Sciences, Engineering, and Medicine
NDF	Neutral detergent fiber
NEl	Net energy for lactation
NFFS	Non-forage fiber sources

Acronym	Description
NIV	Nivalenol
NP	Nasopharyngeal
NPN	Nonprotein nitrogen
NRC	National Research Council
NSC	Non-structural carbohydrate
OBCFA	Odd- and branched-chain fatty acids
OT	Ochratoxin
PAMP	Pathogen-associated molecular patterns
paNDF	Physically adjusted neutral detergent fiber
PARL	Particle-associated rumen liquid
PAT	Patulin
PCB	Polychlorinated biphenyls
PCDD	Polychlorinated dibenzodioxins
PCH	Phosphatidylcholines
PCR	Polymerase chain reaction
PDC	Plant defensive chemicals
PEM	Polioencephalomalacia
peNDF	Physically effective neutral detergent fiber
PIR	Potential intake rate
PLPF	Proportion of large particles in feed
PMR	Partially mixed ration
PRR	Pattern recognition receptor
PUFA	Polyunsaturated fatty acids
RDP	Rumen degradable protein
RNA	Ribonucleic acid
ROQ-C	Roquefortine C
ROS	Reactive oxygen species
RR	Reticulorumen
rRNA	Ribosomal ribonucleic acid
RUP	Rumen undegradable protein
SAA	Serum amyloid A
SARA	Subacute ruminal acidosis
SCFA	Short-chain fatty acids
SCFP	*Saccharomyces cerevisiae* fermentation product
SF_6	Sulfur hexafluoride
SR	Small ruminants
STEC	Shiga toxin-producing *Escherichia coli*
STG	Sterigmatocystin
TC	Trichothecenes
TCA	Tricarboxylic acid cycle, citric cycle, or Szent-Györgyi-Krebs cycle
TCDD	2,3,7,8-Tetrachlorodibenzo-p-dioxin
THI	Temperature-humidity index
TLR	Toll-like receptors
TMR	Totally mixed ration
TTA	Trans-tracheal aspiration
uNDF	Undigestible neutral detergent fiber
VFA	Volatile fatty acids
VLDL	Very low-density lipoproteins
VTEC	Verocytotoxigenic *Escherichia coli*
WHO	World Health Organization
WSC	Water-soluble carbohydrate

Acronym	Description
ZEN	Zearalenone