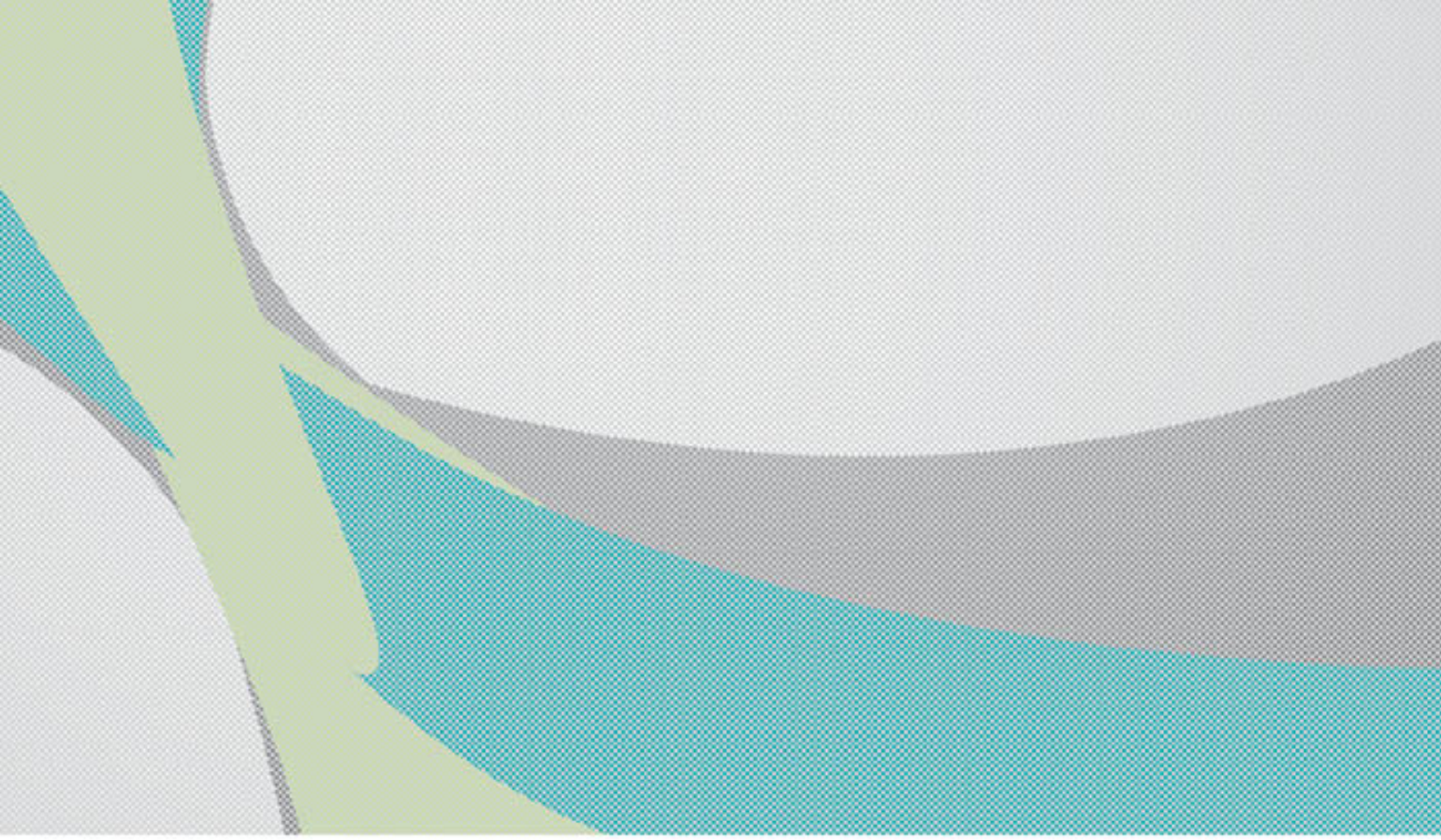

5th edition

Morgan & Mikhail's CLINICAL ANESTHESIOLOGY

John F. Butterworth • David C. Mackey • John D. Wasnick

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Morgan & Mikhail

Anestesiol klinis

FIFTHEDITION

John F. Butterworth IV, MD

Profesor dan Ketua Departemen
Anestesiologi
Virginia Commonwealth University School of Medicine VCU Sistem
Kesehatan Richmond, Virginia

David C. Mackey, MD

Profesor
Departemen Anestesiologi dan perioperatif Kedokteran Universitas Texas
MD Anderson Cancer Center di Houston, Texas

John D. Wasnick, MD, MPH

Steven L. Berk Diberkahi Chair untuk Keunggulan dalam Kedokteran
Profesor dan Ketua Departemen Anestesi Tech Texas Health Sciences
University Center School of Medicine Lubbock, Texas

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Isi

Bab Penulis

Gabriele Baldini, MD, MSc
Asisten Profesor Departemen
Anestesi McGill University
Montreal, Quebec

John F. Butterworth IV, MD
Profesor dan Ketua Departemen
Anestesiologi
Virginia Commonwealth University School of Medicine VCU Sistem
Kesehatan Richmond, Virginia

Francesco Carli, MD, MPhil
Profesor
Departemen Anestesi McGill
University Montreal, Quebec

Charles E. Cowles, Jr, MD
Asisten profesor
Departemen Anestesiologi
dan perioperatif Kedokteran Kepala
Keamanan Offi cer perioperatif
Kewirausahaan
University of Texas MD Anderson Cancer Center di Houston,
Texas

Michael A. FROLICH, MD, MS
associate Professor
Departemen Anestesiologi University of
Alabama di Birmingham Birmingham,
Alabama

Martin Giesecke, MD
MT “Lada” Jenkins Profesor di Anestesiologi Wakil Ketua,
Universitas Rumah Sakit
Departemen Anestesiologi dan Manajemen Sakit University of
Texas Southwestern Medical Center di Dallas, Texas

Srikanth Hosur, MBBS, MD
Konsultan Intensive Care
QuestCare intensivists Dallas,
Texas

Brian M. Ilfeld, MD, MS
Profesor, In Residence Departemen
Anestesiologi University of California, San
Diego San Diego, California

David C. Mackey, MD
Profesor
Departemen Anestesiologi dan
Perioperatif Kedokteran Universitas Texas MD Anderson
Cancer Center di Houston, Texas

Sarah J. Madison, MD
Asisten Profesor Klinis Anestesiologi Departemen
Anestesiologi University of California, San Diego
San Diego, California

Edward R. Mariano, MD, MAS (Penelitian Klinis)
Associate Professor Anestesi Stanford University School of Medicine
Kepala, Anestesiologi dan perioperatif Care Service VA Palo Alto
Sistem Perawatan Kesehatan Palo Alto, California

Brian P. McGlinch, MD
Associate Professor Departemen
Anestesiologi Mayo Clinic Rochester,
Minnesota

Kolonel, Amerika Serikat Cadangan Angkatan Darat, Korps Medis 452 Tempur
Dukungan Rumah Sakit Fort Snelling, Minnesota

Michael Ramsay, MD, FRCA
Ketua Departemen Anestesiologi
dan Sakit Baylor University Medical
Center Presiden Baylor Research
Institute Clinical Professor

University of Texas Southwestern Medical Sekolah Dallas,
Texas

Richard W. Rosenquist, MD
Ketua Departemen Manajemen Nyeri
Anestesiologi Institute Cleveland Clinic
Cleveland, Ohio

Bruce M. Vrooman, MD
Departemen Sakit Anestesiologi
Institute Cleveland Clinic Cleveland,
Ohio

John D. Wasnick, MD, MPH
Steven L. Berk Diberkahi Chair untuk
Keunggulan dalam Kedokteran Profesor dan Ketua
Departemen Anestesi Tech Texas Health Sciences
University Center School of Medicine Lubbock, Texas

kontributor

Kallol Chaudhuri, MD, PhD
Profesor
Departemen Anestesi
Texas Tech University Health Sciences Centre Lubbock, Texas

Swapna Chaudhuri, MD, PhD
Profesor
Departemen Anestesi
Texas Tech University Health Sciences Centre Lubbock, Texas

John Emhardt, MD
Departemen Anestesi
Indiana University School of Medicine
Indianapolis, Indiana

Suzanne N. Escudier, MD
Associate Professor
Departemen Anestesi
Texas Tech University Health Sciences Centre Lubbock, Texas

Aschraf N. Farag, MD
Asisten Profesor Departemen
Anestesi
Texas Tech University Health Sciences Centre Lubbock, Texas

Herbert Gonzalez, MD
Asisten Profesor Departemen
Anestesi
Texas Tech University Health Sciences Centre Lubbock, Texas

Kyle Gunnerson, MD
Departemen Anestesiologi VCU
School of Medicine Richmond,
Virginia

Robert Johnston, MD
Associate Professor Departemen Anestesi Tech Texas
Health Sciences University Center Lubbock, Texas

Sanford Littwin, MD
Asisten Profesor Departemen Roosevelt Hospital Center
dan Columbia Anestesiologi St Luke

University College of Dokter dan Ahli Bedah New York,
New York

Alina Nicoara, MD
Asisten Profesor Departemen
Anestesiologi Duke University Medical
Center di Durham, North Carolina

Bettina Schmitz, MD, PhD
Associate Professor Departemen Anestesi Tech Texas
Health Sciences University Center Lubbock, Texas

Steven L. Shafer, MD
Departemen Anestesi Stanford University
School of Medicine Palo Alto, California

Christiane Vogt-Harenkamp, MD, PhD
Asisten Profesor Departemen Anestesi Tech Texas
Health Sciences University Center Lubbock, Texas

Gary Zaloga, MD
Kedokteran Global Aff mengudara
Baxter Healthcare Deerfi
lapangan, Illinois

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Penelitian dan Ulasan

Jacqueline E. Geier, MD
Resident, Departemen Anestesiologi St Luke Roosevelt Hospital Centre New York, New York

Brian Hirsch, MD
Resident, Departemen Anestesiologi Texas Tech University Medical Center Lubbock, Texas

Shane Huff manusia, MD
Resident, Departemen Anestesiologi Texas Tech University Medical Center Lubbock, Texas

Rahul K. Mishra, MD
Resident, Departemen Anestesiologi Texas Tech University Medical Center Lubbock, Texas

Cecilia N. Pena, MD
Pusat Medis warga, Departemen Anestesiologi Texas Tech University Hospital Lubbock, Texas

Charlotte M. Walter, MD
Resident, Departemen Anestesiologi Texas Tech University Medical Center Lubbock, Texas

Karvier Yates, MD
Resident, Departemen Anestesiologi Texas Tech University Medical Center Lubbock, Texas

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Kata pengantar

Sedikit lebih dari 25 tahun yang lalu, Alexander Kugushev, maka editor untuk Lange Medical Publications, mendekati kami untuk mempertimbangkan menulis buku tory pengantar dalam spesialisasi anestesi yang akan menjadi bagian dari seri Lange populer buku kal medi-. Pak Kugushev terbukti menjadi salesman meyakinkan, sebagian oleh off kenai pengalamannya dengan skor penulis, semuanya berpendapat bahwa prestasi karir yang paling memuaskan mereka adalah peran ayah dari teks-teks mereka. Kami tidak bisa setuju.

Sekarang dalam edisi kelima, secara keseluruhan tujuan gaya dari *Anestesiologi klinis* tetap tidak berubah: yang akan ditulis hanya cukup sehingga mahasiswa kedokteran tahun ketiga dapat memahami semua konsep dasar penting, namun cukup komprehensif untuk memberikan landasan yang kuat bagi penduduk di anestesiologi. Kutipan
C. Philip Larson, Jr, MD dari Kata Pengantar dari edisi pertama: "Teks lengkap; apa-apa dari quence quence dihilangkan. Gaya penulisan adalah tepat, cise con- dan sangat mudah dibaca."

Edisi kelima fitur tiga bab baru: Rawat Jalan, Tidak beroperasi Room, dan Office- Anestesi berdasarkan; Perioperatif Sakit dan Enhanced Hasil; dan Keamanan, Mutu, dan Peningkatan Kinerja. Ada kira--kira 70 angka baru dan 20 meja baru. Tion adop- penuh warna dramatis meningkatkan daya tarik estetika setiap halaman.

Namun, perubahan terbesar dan paling penting dalam edisi kelima adalah "lewat tongkat" untuk tim dibedakan dan dicapai penulis dan editor. Kami sangat senang untuk belajar bahwa Drs. Butterworth, Mackey, dan Wasnick akan berhasil kita. Hasil kerja keras mereka membuktikan antusiasme kami dibenarkan karena mereka telah mengambil

Anestesiologi klinis ke tingkat yang baru. Kami berharap Anda, para pembaca, setuju!

G. Edward Morgan, Jr, MD
Maged S. Mikhail, MD

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Kata pengantar

Penulis harus bangga setiap kali sebuah buku suf- fi sien sukses membutuhkan edisi baru. Th ini terutama terjadi ketika sebuah buku yang konsisten ity dipopulerkan dari waktu ke waktu mengarah ke suksesi penulis asli oleh satu set baru penulis. Th adalah sikap circum- terakhir adalah kasus untuk fi ft h edisi apa yang paling kita sebut "Morgan dan Mikhail." Kami berharap bahwa Anda pembaca akan fi nd edisi baru ini sebagai dibaca dan berguna sebagai Anda telah menemukan sebelumnya empat edisi pekerjaan.

edisi kelima ini, sementara tetap mempertahankan unsur di penting dari pendahulunya, merupakan revisi yang signifikan dari teks. Hanya mereka yang telah menulis sebuah buku dari ukuran dan kompleksitas akan memahami betapa banyak usaha yang terlibat. Sepenuhnya mata pelajaran baru (misalnya, perioperatif Sakit dan Enhanced Hasil) telah ditambahkan, dan banyak topik lainnya yang sebelumnya tinggal di beberapa bab telah dipindahkan dan konsolidasi. Kami telah mencoba untuk melenyapkan redudansi nate dan kontradiksi. Jumlah ilustrasi yang ditujukan untuk anestesi regional dan analgesia telah sangat meningkat untuk memadai mengatasi berkembang pesat pentingnya topik manajemen perioperatif ini. Kejelasan ilustrasi juga ditingkatkan dengan meluasnya penggunaan warna dalam buku ini.

- **Konsep kunci** terdaftar pada awal setiap bab dan sesuai bernomor ikon identifi es bagian (s) dalam bab di mana setiap konsep dibahas. Th ESE harus membantu fokus pembaca pada konsep penting yang mendasari inti dari anestesiologi.
- **kasus Diskusi** menangani masalah klinis bunga saat ini dan dimaksudkan untuk merangsang diskusi dan pemikiran kritis.
- Th e disarankan membaca telah direvisi dan diperbarui untuk menyertakan alamat Web yang bersangkutan dan referensi untuk pedoman praktek klinis dan parameter latihan. Kami belum mencoba untuk memberikan daftar lengkap referensi: kami berharap bahwa sebagian besar pembaca teks ini biasanya akan melakukan pencarian literatur mereka sendiri pada topik medis menggunakan Google, PubMed, dan sumber daya lainnya elektronik. Memang, kami berharap bahwa segmen yang terus meningkat dari pembaca kami akan mengakses teks ini dalam salah satu dari beberapa bentuk elektronik.

- Beberapa ilustrasi baru dan gambar telah ditambahkan ke edisi ini. Meskipun demikian, tujuan kami tetap sama seperti yang dari edisi pertama: "untuk memberikan, presentasi konsisten singkat dari prinsip-prinsip dasar penting untuk praktik modern anestesi."

Kami ingin mengucapkan terima kasih Brian Belval, Harriet Lebowitz, dan Marsha Loeb untuk bantuan yang tak ternilai.

Meskipun niat terbaik kami, berbagai kesalahan mungkin telah membuat jalan mereka ke dalam edisi kelima. Kami akan berterima kasih kepada pembaca yang melaporkan ini kepada kami di mm5edition@gmail.com sehingga kita bisa memperbaikinya di cetak ulang dan edisi mendatang.

John F. Butterworth IV, MD
David C. Mackey, MD John
D. Wasnick, MD, MPH

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BAB

11

Praktik Anestesiologi

TS CON KEY

Oliver Wendell Holmes pada tahun 1846 adalah yang pertama untuk mengusulkan penggunaan istilah *anestesi* untuk menunjukkan negara yang menggabungkan amnesia, analgesia, dan narkosis untuk membuat operasi tanpa rasa sakit mungkin.

Eter digunakan untuk tujuan sembrono (“frolics eter”) dan tidak digunakan sebagai agen anestesi pada manusia sampai 1842, ketika Crawford
W. panjang dan William E. Clark independen digunakan pada pasien. Pada tanggal 16 Oktober, 1846, William TG Morton dilakukan yang pertama dipublikasikan demonstrasi anestesi umum untuk operasi bedah menggunakan eter. Aplikasi asli dari anestesi lokal modern dikreditkan ke Carl Koller, pada saat rumah o FFI cer dalam oftalmologi, yang menunjukkan anestesi topikal mata dengan kokain pada tahun 1884.

4 Curare sangat difasilitasi intubasi trakea dan relaksasi otot selama operasi. Untuk pertama kalinya, operasi dapat dilakukan pada pasien tanpa persyaratan bahwa tingkat yang relatif jauh dari inhalasi anestesi umum digunakan untuk menghasilkan relaksasi otot. John Snow, sering dianggap sebagai ayah dari anestesi khusus, adalah yang pertama untuk secara ilmiah
5 menyelidiki eter dan fisiologi anestesi umum.

6 “Kapten kapal” doktrin, yang diselenggarakan ahli bedah yang bertanggung jawab untuk setiap aspek perawatan perioperatif pasien (termasuk anestesi), tidak lagi gagasan valid ketika ahli anestesi hadir.

Th e filsuf Yunani Dioscorides pertama menggunakan istilah *anestesi* dalam AD fi abad pertama untuk menggambarkan Ects eff narkotika seperti dari mandragora tanaman. Th e jangka selanjutnya yang Defi ned di Bailey *Sebuah Universal Etimologi English Dictionary (* 1721) sebagai “cacat sensasi” dan lagi di *Encyclopedia Britannica (* 1771) sebagai “kekurangan indra.” Oliver Wendell Holmes pada tahun 1846 adalah yang pertama untuk mengusulkan penggunaan istilah untuk menunjukkan keadaan yang menggabungkan amnesia, analgesia, dan narkosis untuk membuat operasi tanpa rasa sakit mungkin. Di Amerika Serikat, penggunaan istilah *anestesiologi* untuk menunjukkan praktek atau studi anestesi pertama diusulkan di dekade kedua abad kedua puluh untuk menekankan tumbuh scientifi c dasar yang khusus.

Meskipun anestesi sekarang bertumpu pada fondasi scientifi c sebanding dengan ikatan khusus-lain, praktek anestesi masih sangat banyak campuran ilmu pengetahuan dan seni. Selain itu, praktek ini telah berkembang jauh melampaui render pasien insen- sible nyeri selama operasi atau pengiriman obstetrik (tabel 1-1). Th e khusus unik membutuhkan kerja-ing keakraban dengan daftar panjang spesialisasi lain, termasuk operasi dan subspesialisasi yang, kedokteran internal, pediatri, dan kebidanan serta farmakologi klinis, diterapkan fisiologi, dan biomedis

TABLE 1•1 Definisi dari praktek anestesi dalam praktek kedokteran. [1]

Pengkajian dan penyusunan pasien untuk operasi dan anestesi.
Pencegahan, diagnosis, dan pengobatan nyeri selama dan setelah prosedur bedah, kebidanan, terapi, dan diagnostik.
perawatan akut pasien selama periode perioperatif.
Diagnosis dan pengobatan penyakit kritis.
Diagnosis dan pengobatan akut, kronis, dan nyeri cancerrelated.
Jantung, paru, dan resusitasi trauma.
Evaluasi fungsi pernapasan dan penerapan perawatan dalam terapi pernapasan.
Instruksi, evaluasi kinerja, dan pengawasan baik tenaga medis dan paramedis yang terlibat dalam perawatan perioperatif.
Administrasi di fasilitas pelayanan kesehatan, organisasi, dan sekolah medis yang diperlukan untuk melaksanakan tanggung jawab tersebut.
Perilaku klinis, translasi, dan penelitian ilmu dasar.

[1] Data dari American Board of Anestesiologi Booklet Informasi, Februari 2012.

teknologi. Kemajuan terbaru dalam biomedis technol- ogy, neuroscience, dan farmakologi terus membuat anestesi sebuah intelektual merangsang dan berkembang pesat khusus. Banyak dokter memasuki posisi residensi di anestesiologi sudah akan memiliki beberapa tahun pendidikan kedokteran pascasarjana dan kation bahkan mungkin Certifi dalam spesialisasi medis lainnya.

Th adalah bab ulasan sejarah anestesi, menekankan akar Inggris dan Amerika, serta menganggap ruang lingkup saat ini yang khusus.

Sejarah Anestesi

Th e khusus anestesi dimulai pada abad kesembilan belas pertengahan dan menjadi dengan tegas didirikan kurang dari enam dekade lalu. peradaban kuno telah menggunakan opium poppy, daun coca, mandrake root, alkohol, dan bahkan phlebotomy (ke titik sciousness uncon-) untuk memungkinkan ahli bedah untuk beroperasi. Mesir kuno menggunakan kombinasi opium poppy (mengandung morfin) dan hyocyamus (mengandung skopolamin); kombinasi yang sama, morfin dan skopolamin, telah digunakan secara parenteral untuk premedikasi. Apa yang berlalu untuk anestesi regional di zaman kuno terdiri dari kompresi batang saraf (iskemia saraf) atau penerapan dingin (cryoanalgesia). e Inca th mungkin telah berlatih anestesi lokal sebagai dokter bedah mereka mengunyah daun koka dan diterapkan ke luka operasi, khususnya sebelum trephining untuk sakit kepala.

Th e evolusi bedah modern terhambat tidak hanya oleh pemahaman yang buruk tentang cesses penyakit pro, anatomi, dan asepsis bedah tetapi juga oleh kurangnya teknik anestesi yang handal dan aman. Th teknik ese berkembang pertama dengan anestesi inhalasi, diikuti oleh anestesi lokal dan regional, dan akhirnya anestesi intravena. pengembangan e th anestesi bedah dianggap salah satu penemuan paling penting dalam sejarah manusia.

anestesi inhalasi

Karena jarum suntik tidak ditemukan sampai 1855, fi anestesi pertama umum yang des-tined menjadi agen inhalasi. Dietil eter (dikenal pada saat itu sebagai “eter sulfat” karena itu pro diperkenalkan oleh reaksi kimia sederhana antara etil alkohol dan asam sulfat) aslinya dibuat dalam

1540 oleh Valerius Cordus. Eter digunakan untuk tujuan semb rono (“frolics eter”), tapi tidak sebagai agen anestesi pada manusia sampai 1842, ketika Crawford W. panjang dan William E. Clark indepen- dently digunakan pada pasien untuk operasi dan ekstraksi gigi, masing-masing. Namun, mereka tidak pub-licize penemuan mereka. Empat tahun kemudian, di Boston, pada 16 Oktober, 1846, William TG Morton dilakukan yang pertama dipublikasikan demonstrasi umum thesia anes- untuk operasi bedah menggunakan eter. Th e dra- sukses matic pameran yang dipimpin ahli bedah operasi untuk berseru kepada khalayak skeptis: “! Laki-laki Gentle-, ini tidak bohong”

Kloroform secara independen disiapkan oleh von Leibig, Guthrie, dan Soubeiran pada tahun 1831. Meskipun pertama digunakan oleh Holmes Coote pada tahun 1847,

kloroform diperkenalkan ke dalam praktek klinis oleh Scot Sir James Simpson, yang diberikan kepada pasien untuk mengurangi rasa sakit persalinan. Ironisnya, Simpson telah hampir ditinggalkan medis prac- Tice er belakang nya menyaksikan putus asa mengerikan dan penderitaan pasien yang menjalani operasi tanpa anestesi.

Joseph Priestley diproduksi nitrous oxide di 1772, dan Humphry Davy pertama mencatat sifat analgesik pada tahun 1800. Gardner Colton dan Horace Wells dikreditkan dengan memiliki pertama digunakan nitrous oxide sebagai anestesi untuk ekstraksi gigi pada manusia di kurangnya 1844. Nitrous oxide ini potensi (80% nitrous oxide hasil konsentrasi dalam sia analge- tapi anestesi tidak bedah) menyebabkan onstrations dem- klinis yang kurang meyakinkan dibandingkan dengan eter.

Nitrous oxide adalah yang paling populer dari tiga anestesi inhalasi awal karena potensi yang rendah dan kecenderungan untuk menyebabkan asfiksia ketika digunakan sendiri (lihat Bab 8). Minat nitrous oxide dihidupkan kembali pada 1868 ketika Edmund Andrews diberikan dalam 20% oksigen; penggunaannya adalah, bagaimana- pernah, dibayangi oleh popularitas eter dan kloroform. Ironisnya, nitrous oxide adalah satu-satunya dari tiga agen ini masih digunakan secara luas hari ini. Kloroform digantikan eter dalam popularitas di banyak daerah (terutama di Inggris), namun laporan dari aritmia jantung yang berhubungan dengan kloroform, depresi pernafasan, dan hepatotoksisitas akhirnya untuk menyebabkan praktisi untuk meninggalkannya mendukung eter, khususnya di Amerika Utara.

Bahkan belakang er pengenalan anestesi lainnya inhala- tion (etil klorida, etilen, divinil eter, siklopropana, trichloroethylene, dan fl urox- ene), eter tetap standar sintetik anes- inhalasi sampai awal 1960-an. Th e satunya agen inhalasi yang disaingi keselamatan eter dan popularitas adalah siklopropana (diperkenalkan pada tahun 1934). Namun, keduanya sangat mudah terbakar dan keduanya telah sejak diganti dengan suksesi nonfl mudah terbakar ampuh fl hidrokarbon uorinated: halotan (dikembangkan pada tahun 1951; dirilis pada 1956), methoxyfl URANE (dikembangkan pada tahun 1958; dirilis pada 1960), enfl URANE (dikembangkan pada tahun 1963; dirilis pada tahun 1973), dan URANE isofl (dikembangkan pada tahun 1965; dirilis pada tahun 1981).

Dua agen baru sekarang yang lar paling ketenarannya di negara-negara maju. Desfl URANE (dirilis pada tahun 1992), memiliki banyak sifat-sifat yang diinginkan dari URANE isofl serta serapan lebih cepat dan bangsa menghilangkan adanya (hampir secepat nitrous oksida). Sevofl u- rane, memiliki kelarutan darah rendah, tetapi kekhawatiran tentang potensi toksisitas produk degradasi tertunda peluncurannya di Amerika Serikat sampai tahun 1994 (lihat Bab 8). kekhawatiran th ese telah terbukti sebagian besar teoritis, dan URANE sevofl, tidak desfl URANE, telah menjadi yang paling banyak digunakan inhalasi anes- sintetik di Amerika Serikat, sebagian besar menggantikan Thane halo- dalam praktek pediatrik.

LOKAL & DAERAH Anestesi

e kualitas obat th coca telah digunakan oleh suku Inca selama berabad-abad sebelum tindakannya yang pertama diamati oleh orang Eropa. Kokain diisolasi dari daun koka pada tahun 1855 oleh Gaedicke dan purifi ed di

1860 oleh Albert Niemann. Th e asli tion applica- anestesi lokal modern dikreditkan ke Carl Koller, pada saat sebuah cer rumah pejabat di mology ophthal-, yang menunjukkan anestesi topikal mata dengan kokain pada tahun 1884. Kemudian pada tahun 1884 William Hal- sted digunakan kokain untuk intradermal infi filtrasi dan blok saraf (termasuk blok saraf wajah, pleksus brakialis, saraf pudenda, dan pos terior saraf tibialis). Agustus Bier dikreditkan dengan administrasi fi anestesi spinal pertama pada tahun 1898. Dia juga yang pertama untuk menggambarkan anestesi regional intravena (Bier block) pada tahun 1908. Prokain disintesis pada tahun 1904 oleh Alfred Einhorn dan dalam waktu satu tahun digunakan secara klinis sebagai lokal anestesi oleh Heinrich Braun. Braun juga yang pertama untuk menambahkan epinefrin ke pro durasi panjang anestesi lokal. Ferdinand Cathelin dan Jean Sicard memperkenalkan anestesi epidural ekor pada tahun 1901. Lumbar anestesi epidural digambarkan pertama pada tahun 1921 oleh Fidel Pages dan lagi (independen) pada tahun 1931 oleh Achille Dogliotti. Addi anestesi lokal tional kemudian diperkenalkan meliputi dibucaine (1930), tetracaine (1932), caine lido- (1947), kloroprokain (1955), mepivacaine (1957), prilocaine (1960), bupivakain (1963), dan etidocaine (1972) . e penambahan terbaru Th, vacaine ropi- dan levobupivacaine, memiliki durasi aksi yang mirip dengan bupivakain tapi ity beracun kurang jantung (lihat Bab 16). caine lido- (1947), kloroprokain (1955), mepivacaine (1957), prilocaine (1960), bupivakain (1963), dan etidocaine (1972). e penambahan terbaru Th, vacaine ropi- dan levobupivacaine, memiliki durasi aksi yang mirip dengan bupivakain tapi ity beracun kurang jantung (lihat Bab 16). caine lido- (1947), kloroprokain (1955), mepivacaine (1957), prilocaine (1960), bupivakain (1963), dan etidocaine (1972). e penambahan terbaru Th, vacaine ropi- dan levobupivacaine, memiliki durasi aksi yang mirip dengan bupivakain tapi ity beracun kurang jantung (lihat Bab 16).

ANESTESI INTRAVENA

induksi Agen

anestesi intravena diperlukan penemuan jarum suntik dan jarum oleh Alexander Wood pada tahun 1855. upaya awal pada anestesi intravena termasuk penggunaan kloral hidrat (oleh bijih pada tahun 1872), kloroform dan eter (Burkhardt pada tahun 1909), dan kombinasi morfin dan skopolamin (Bredenfeld pada tahun 1916). Barbiturat yang pertama synthe- berukuran tahun 1903 oleh Fischer dan von Mering. Th e pertama barbiturat digunakan untuk induksi anestesi adalah asam diethylbarbituric (barbital), tapi itu tidak sampai diperkenalkannya hexobarbital pada tahun 1927 bahwa induksi barbiturat menjadi populer. Th iopental, syn-thesized pada tahun 1932 oleh Volwiler dan Tabern, itu pertama digunakan secara klinis oleh John Lundy dan Ralph Waters pada tahun 1934 dan selama bertahun-tahun tetap agen mon paling com- untuk induksi intravena anestesi.

K. Stoelting dan merupakan satu-satunya barbiturat lain yang digunakan untuk induksi anestesi pada manusia. Buritan er chlor-diazepoxide ditemukan pada tahun 1955 dan dirilis untuk penggunaan klinis pada tahun 1960, diazepam benzodiazepines- lainnya, lorazepam, midazolam dan-datang yang akan digunakan secara ekstensif untuk premedikasi, sedasi sadar, dan induksi anestesi umum. Ket- amina disintesis pada tahun 1962 oleh Stevens dan pertama digunakan secara klinis pada tahun 1965 oleh Corssen dan Domino; dirilis pada tahun 1970 dan terus menjadi populer saat ini, khususnya bila diberikan dalam tion combina- dengan agen lainnya. Etomidate disintesis pada tahun 1964 dan dirilis pada tahun 1972. antusiasme awal atas kurangnya relatif dari peredaran darah dan pernafasan Ects eff marah oleh bukti supresi adrenal, dilaporkan belakang er bahkan dosis tunggal. Th e rilis pofol pro di 1986 (1989 di Amerika Serikat) adalah kemajuan besar dalam anestesi rawat jalan karena durasi pendek tindakan (lihat Bab 9). Propofol adalah yang ditonton rently agen yang paling populer untuk tion induc- intravena di seluruh dunia.

Agen Pemblokiran neuromuskular

e pengenalan Th curare oleh Harold Griffi th dan Enid Johnson pada tahun 1942 merupakan tonggak sejarah dalam anestesi.

Curare sangat difasilitasi intubasi trakea dan relaksasi otot selama operasi. Untuk fi waktu pertama, operasi dapat dilakukan pada pasien tanpa persyaratan bahwa tingkat yang relatif jauh dari inhalasi anestesi umum digunakan untuk menghasilkan relaksasi cle mus-. dosis besar seperti anestesi sering en mengakibatkan kardiovaskular berlebihan dan depresi pernafasan serta munculnya berkepanjangan. Lebih-lebih, dosis yang lebih besar yang sering en tidak ditoleransi oleh pasien lemah.

Suksinilkolin disintesis oleh Bovet pada tahun 1949 dan dirilis pada tahun 1951; telah menjadi agen dard-standar untuk memfasilitasi intubasi trakea selama induksi urutan cepat. Sampai saat ini, kolin succinyl- tetap tak tertandingi di onset yang cepat relaksasi otot yang mendalam, tetapi ects sisi eff nya diminta mencari pengganti yang sebanding. blocker lainnya neuromuskuler (NMBS; dibahas dalam Bab 11) -gallamine, decamethonium, metocu- rine, alcuronium, dan pancuronium-yang subse- quently diperkenalkan. Sayangnya, agen ini adalah sering en terkait dengan Ects sisi eff (lihat Bab 11), dan pencarian untuk NMB yang ideal terus. Baru-baru ini memperkenalkan agen yang lebih mirip sebuah NMB yang ideal meliputi vekuronium, atracurium, rocuronium, dan *cis* - atracurium.

opioid

Morfin, diisolasi dari opium pada tahun 1805 oleh Sertürner, juga mencoba sebagai obat bius intravena. Th e efek samping yang berhubungan dengan dosis besar opioid dalam laporan awal menyebabkan banyak ahli anestesi untuk menghindari opioid dan mendukung anestesi inhalasi murni. est antar dalam opioid dalam anestesi dikembalikan setelah sintesis dan pengenalan meperidine pada tahun 1939. e konsep Th dari *anestesi yang seimbang* diperkenalkan pada tahun 1926 oleh Lundy dan lain-lain dan berevolusi untuk mencakup thiopental untuk induksi, nitrous oxide untuk amne- sia, opioid untuk analgesia, dan curare untuk relaksasi otot. Pada tahun 1969, Lowenstein menghidupkan kembali minat dalam “murni” anestesi opioid dengan memasukkan konsep dosis besar opioid sebagai thetics anes- lengkap. Morfin adalah agen pertama fi sehingga bekerja, tetapi fentanyl dan sufentanil telah disukai oleh margin besar sebagai agen tunggal. Seperti pengalaman tumbuh dengan teknik ini, beberapa keterbatasan-unreliably yang mencegah kesadaran pasien, tidak lengkap dukungan- menekan respon otonom selama operasi, dan berkepanjangan depresi-yang pernapasan direalisasikan.

Remifentanil, subjek opioid untuk degradasi cepat oleh plasma nonspecifi c dan esterase jaringan, memungkinkan tingkat mendalam analgesia opioid untuk dipekerjakan tanpa kekhawatiran mengenai kebutuhan untuk ventilasi tive postopera-.

EVOLUSI KEISTIMEWAAN THE

Origins Inggris

Berikut fi demonstrasi publik pertama di Amerika Serikat, anestesi ether cepat diadopsi

di Inggris. John Snow, sering en dianggap sebagai ayah dari anestesi khusus, adalah yang pertama dokter untuk mengambil bunga penuh waktu di anestesi baru ini. Dia adalah yang pertama untuk scientifi Cally investigasi gerbang eter dan fisiologi anestesi umum. Tentu saja, Salju juga pelopor dalam ogy epidemiol-. Dia membantu menghentikan epidemi kolera di London dengan membuktikan bahwa agen penyebab ditularkan oleh konsumsi air sumur terkontaminasi daripada jika terhirup. Pada 1847, Salju menerbitkan buku pertama pada anestesi umum, *Di Menghirup Eter* . Ketika sifat anestesi bentuk kloro- dibuat dikenal, ia dengan cepat menyelidiki dan mengembangkan inhaler untuk agen itu juga. Dia percaya bahwa obat semprot harus digunakan dalam tering eter adminis- atau kloroform untuk mengontrol dosis obat bius. Buku kedua, *Pada Kloroform dan Anestesi Lain* . diterbitkan posthu- mously pada tahun 1858.

kematian belakang er Snow, Dr. Joseph T. Clover mengambil tempat sebagai anestesi terkemuka Inggris. Clover ditekankan terus memantau nadi pasien selama anestesi, sebuah praktek yang belum standar pada saat itu. Dia adalah yang pertama untuk menggunakan manuver jaw-dorong untuk menghilangkan napas obstruc- tion, yang pertama bersikeras bahwa peralatan resusitasi selalu tersedia selama anestesi, dan yang pertama untuk menggunakan kanula krikotiroid (untuk menyelamatkan pasien dengan oral tumor yang mengembangkan cara obstruksi ber lengkap). Buritan er Clover, Sir Frederic Hewitt menjadi ahli anestesi terkemuka Inggris pada pergantian abad terakhir. Dia bertanggung jawab untuk banyak tions inven-, termasuk jalan napas oral. Hewitt juga menulis apa yang banyak mempertimbangkan untuk menjadi yang pertama buku sejati anestesi, yang pergi melalui lima edisi. Salju, Clover, dan Hewitt mendirikan tradisi anestesi sician phy- di Inggris. Pada tahun 1893, organisasi pertama dari spesialis dokter di anestesi, London Society of Dokter-dokter anestesi, dibentuk di Inggris oleh JF Silk.

Th e pertama elektif trakea intubasi selama anestesi dilakukan pada akhir abad kesembilan belas oleh ahli bedah Sir William Macewen di tanah Scot-, Joseph O'Dwyer di Amerika Serikat, dan Franz Kuhn di Jerman. Intubasi trakea selama anestesi dipopulerkan di Inggris oleh Sir Ivan Magill dan Stanley Rowbotham pada tahun 1920.

Origins Amerika

Di Amerika Serikat, hanya beberapa dokter telah dengan spesialisasi cialized dalam anestesi oleh 1900. Th e tugas provid- ing anestesi umum itu sering en didelegasikan kepada junior petugas bedah rumah pejabat atau mahasiswa kedokteran, jika mereka tersedia.

Th e organisasi pertama dari anestesi dokter di Amerika Serikat adalah Long Island Society of Dokter-dokter anestesi dibentuk pada tahun 1905, yang, seperti tumbuh, berganti nama menjadi New York Society of Dokter-dokter anestesi di 1911. Th e Internasional Anestesi Penelitian ologists ety (IARS) didirikan pada tahun 1922, dan pada tahun yang sama dengan IARS disponsori scientifi c jurnal *Penelitian saat ini di Anestesi dan Analgesia (* sekarang disebut *Anestesi dan Analgesia)* mulai diterbitkan. Di 1936, New York Society of Dokter-dokter anestesi menjadi American Society of Dokter-dokter anestesi, dan kemudian, pada 1945, American Society of Anesthesiologists (ASA). Th e scientifi c jurnal *Anestesiologi* adalah pertama diterbitkan pada tahun 1940.

Empat dokter menonjol di devel-opment awal anestesi di Amerika Serikat belakang er 1900: FH McMechan, Arthur E. Guedel, Ralph M. Waters, dan John S. Lundy. McMechan adalah kekuatan pendorong di belakang kedua IARS dan *Penelitian sewa yang ditonton di Anestesi dan Analgesia* . dan tanpa lelah diselenggarakan dokter yang mengkhususkan diri dalam anestesi ke nizations orga- nasional dan internasional sampai kematiannya pada tahun 1939. Guedel adalah yang pertama untuk menggambarkan tanda-tanda dan tahapan anestesi umum. Ia menganjurkan tabung manset ed trakea dan memperkenalkan artifi resmi ventilasi selama anestesi ether (kemudian disebut *respirasi dikendalikan* oleh

Waters). Ralph Waters membuat daftar panjang tions kontribusinya untuk khusus, mungkin yang paling penting dari yang desakan di tion educa- yang tepat spesialis di anestesi. Waters mengembangkan fi departemen akademik pertama dari anestesiologi di University of Wisconsin di Madison. Lundy berperan penting dalam pembentukan Dewan Amerika Anestesiologi dan diketuai Bagian American Medical Association pada Anestesiologi selama 17 tahun.

Karena kelangkaan dokter specializ- ing dalam anestesi di Amerika Serikat dan per- relatif aman ceived anestesi eter, ahli bedah baik di Mayo Clinic dan Cleveland Clinic mulai pelatihan dan mempekerjakan perawat sebagai anestesi di awal 1900-an. Sebagai jumlah perawat ahli anestesi meningkat, sebuah organisasi nasional (sekarang disebut American Association of Nurse Dokter-dokter anestesi) didirikan pada tahun 1932. Th e AANA pertama off ered pemeriksaan Certifi kation pada tahun 1945. Pada tahun 1969 program dua Anestesiologi Asisten mulai accept- ing siswa, dan pada tahun 1989 yang pertama Certifi kasi pemeriksaan untuk AAS diberikan. Certifi ed Terdaftar Perawat Dokter-dokter anestesi dan Asisten inti Anesthesiolo- mewakili anggota penting dari tenaga kerja anestesi di Amerika Serikat dan di negara lain.

O FFI resmi Pengakuan

Pada tahun 1889 Henry Yesaya Dorr, seorang dokter gigi, diangkat Profesor dari Praktek Kedokteran Gigi, ics Anaesthet- dan Anestesi di Philadelphia College of Dentistry. Th kita ia adalah yang pertama dikenal profesor anestesi di seluruh dunia. Th Omas D. Buchanan, dari New York Medical College, adalah yang pertama dokter yang ditunjuk Profesor Anestesi (pada tahun 1905). Ketika American Board of Anestesiologi didirikan pada tahun 1938, Dr. Buchanan menjabat sebagai presiden pertama nya. Di Inggris, fi pemeriksaan pertama untuk Diploma Anestesi berlangsung pada tahun 1935, dan pertama Chair di Anestesi diberikan kepada Sir Rob- ert Macintosh pada tahun 1937 di Universitas Oxford. thesia Anes- menjadi pejabat secara resmi diakui khusus di Inggris hanya pada tahun 1947, ketika Royal College of Surgeons didirikan Fakultas nya Dokter-dokter anestesi.

Ruang Lingkup Anestesi

Th e praktek anestesi telah berubah secara dramatis sejak zaman John Snow. Th e anesthesi- yang modern ologist sekarang kedua konsultan perioperatif dan seorang pembebas utama perawatan untuk pasien. Secara umum, ahli anestesi mengelola hampir semua “noncutting” aspek perawatan medis pasien di immedi- yang

makan periode perioperatif. Th e “kapten kapal” doktrin, yang diselenggarakan ahli bedah yang bertanggung jawab untuk setiap aspek dari perawatan perioperatif pasien (termasuk anestesi), tidak lagi gagasan valid ketika ahli anestesi hadir. Th e sur- Geon dan ahli anestesi harus berfungsi bersama-sama sebagai tim yang efektif eff, dan keduanya akhirnya Jawaban-bisa pasien daripada satu sama lain.

Th e praktik modern anestesi tidak con fi ned untuk render pasien peka terhadap rasa sakit (Tabel 1-1). Ahli anestesi memantau, tenang, dan memberikan anestesi umum atau regional di luar ruang operasi untuk berbagai prosedur pencitraan, endoskopi, terapi electroconvulsive, dan kateterisasi jantung. Anestesi telah tradition- sekutu menjadi perintis di resusitasi cardiopulmonary dan terus menjadi anggota integral dari tim resusitasi.

Peningkatan jumlah praktisi Pur- menuntut subspesialisasi di anestesi untuk bedah kardiotoraks (lihat Bab 22), perawatan kritis (lihat Bab 57), neuroanesthesia (lihat Bab 27), anestesi obstetri (lihat Bab 41), anestesi pediatrik (lihat Bab 42), dan obat nyeri (lihat Bab

47). persyaratan Certifi kation untuk petence com- khusus dalam perawatan dan sakit kritis kedokteran sudah ada di Amerika Serikat. program Fellowship di Dewasa Jantung Anestesi dan Pediatric Anestesiologi memiliki spesifik c akreditasi KASIH require-, dan segera mereka di Obstetric Anestesiologi akan juga. Pemeriksaan Certifi kation akan segera tersedia di Pediatric Anestesiologi. Pendidikan dan Certifi kation di anestesiologi juga dapat digunakan sebagai dasar untuk Certifi kation di Sleep Medicine atau Kedokteran Paliatif.

Ahli anestesi secara aktif terlibat dalam administrasi dan arah medis banyak fasilitas bedah rawat jalan, ruang operasi suite, unit perawatan intensif, dan terapi pernafasan

departemen. Th ey juga telah mengasumsikan posisi tive dan kepemimpinan Kewenangan pada staf medis s dari banyak rumah sakit dan fasilitas perawatan rawat jalan. Th ey berfungsi sebagai dekan sekolah kedokteran dan inisiatif-inisiatif execu- kepala sistem kesehatan.

DISARANKAN MEMBACA

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BAB 2

operasi yang Room Lingkungan

Charles E. Cowles, MD

TS CON KEY

Tekanan 1000 psig menunjukkan E-silinder yang kira-kira setengah penuh dan mewakili 330 L oksigen. Satu-satunya cara yang dapat diandalkan untuk menentukan volume residu dari nitrous oxide adalah untuk menimbang silinder.

Untuk mencegah lampiran silinder yang salah, produsen silinder telah mengadopsi sistem pin indeks keamanan.

Prinsip dasar keselamatan radiasi adalah untuk menjaga paparan "serendah mungkin praktis" (ALARP). Prinsip-prinsip ALARP adalah perlindungan dari paparan radiasi dengan menggunakan waktu, jarak, dan perisai. Besarnya arus bocor biasanya tak terlihat menyentuh (<1 mA, dan jauh di bawah ambang fi brillation dari 100 mA). Jika saat ini bypasses resistensi yang tinggi o ff ered oleh kulit, bagaimanapun, dan diterapkan secara langsung ke jantung (microshock), saat **serendah 100 µ Sebuah mungkin berakibat fatal. Kebocoran** maksimum yang diperbolehkan dalam peralatan ruang operasi **adalah 10 µ A. Untuk mengurangi kemungkinan dua kesalahan** hidup bersama, garis isolasi langkah-langkah memantau potensi aliran arus dari power supply yang terisolasi ke tanah. Pada dasarnya, monitor jalur isolasi menentukan tingkat isolasi antara dua kabel listrik dan tanah

dan memprediksi jumlah arus yang *bisa*

fl ow jika hubungan pendek kedua adalah untuk

7 mengembangkan. Hampir semua kebakaran bedah dapat dicegah. Tidak seperti komplikasi medis, kebakaran adalah produk dari sifat fisik dan kimia sederhana. Kejadian ini dijamin diberikan kombinasi yang tepat dari faktor, tetapi dapat dihilangkan hampir seluruhnya dengan memahami prinsip-prinsip dasar risiko kebakaran. Kemungkinan faktor risiko yang paling umum untuk bedah kebakaran berkaitan

8 dengan pengiriman terbuka oksigen. Pemberian oksigen konsentrasi lebih besar dari 30% harus dipandu oleh presentasi

9 klinis pasien dan tidak semata-mata oleh protokol atau kebiasaan. Urutan menghentikan gas aliran dan penghapusan tabung endotrakeal ketika kebakaran terjadi di saluran napas tidak sepenting memastikan bahwa kedua tindakan yang

10 dilakukan dengan cepat.

11 Sebelum memulai operasi laser, perangkat laser harus di ruang operasi, tanda-tanda peringatan harus dipasang pada pintu, dan kacamata pelindung harus dikeluarkan. Penyedia anestesi harus memastikan bahwa tanda-tanda peringatan dan kacamata sesuai dengan label pada perangkat laser sebagai perlindungan laser spesifik untuk jenis laser.

Anestesi, yang menghabiskan lebih banyak waktu di operasi kamar dari kelompok lain dari dokter, bertanggung jawab untuk melindungi pasien dan personil kamar operasi dari banyak bahaya dur- ing operasi. Beberapa ancaman yang unik untuk ruang operasi. Akibatnya, ahli anestesi mungkin bertanggung jawab untuk memastikan berfungsinya gas medis ruang operasi, kebakaran tion preven- dan manajemen, faktor lingkungan (misalnya, suhu, kelembaban, ventilasi, dan kebisingan), dan keselamatan listrik. Th e peran ahli anestesi juga dapat mencakup koordinasi atau bantuan dengan lay out dan desain suite bedah, termasuk workfl tambahan ow. Th adalah bab menjelaskan fitur-fitur utama ruang operasi yang menarik khusus untuk ahli anestesi dan potensi bahaya asso- diasosiasikan dengan sistem ini.

Budaya keselamatan

Pasien sering en memikirkan ruang operasi sebagai tempat yang aman di mana perawatan yang diberikan ini berpusat di sekitar melindungi pasien. penyedia medis seperti personel anestesi, dokter bedah, dan perawat bertanggung jawab untuk melaksanakan beberapa tugas penting dengan cepat. Kecuali anggota tim ruang operasi melihat keluar untuk satu sama lain, kesalahan bisa terjadi. Th e cara terbaik untuk mencegah bahaya serius untuk pasien adalah dengan menciptakan budaya keselamatan. Ketika budaya keselamatan eff ectively diterapkan di ruang operasi, tindakan tidak aman dihentikan sebelum bahaya terjadi.

Salah satu alat yang menumbuhkan budaya keselamatan adalah penggunaan checklist keselamatan bedah. checklist tersebut digunakan sebelum insisi pada setiap kasus dan dapat termasuk komponen disepakati oleh fasilitas sebagai penting. Banyak daftar periksa bedah yang berasal dari daftar keselamatan bedah diterbitkan oleh nization Kesehatan Dunia Orga- (WHO). Untuk daftar periksa untuk menjadi efektif eff, mereka harus pertama-tama akan digunakan; kedua, semua anggota tim kal surgi- harus terlibat ketika checklist sedang digunakan. Daftar-pembanding yang efektif paling eff bila dilakukan dalam mode interaktif. Contoh dari checklist kurang optimal dijalankan adalah salah satu yang dibaca secara keseluruhan, er belakang yang ahli bedah menanyakan apakah semua orang setuju. Th format membuatnya diffi kultus untuk mengidentifikasi masalah yang mungkin. Metode yang lebih baik adalah salah satu yang memunculkan respon belakang er setiap titik; misalnya, diikuti oleh “Apakah semua orang setuju kita melakukan penghapusan ginjal kiri?”, dan sebagainya. daftar periksa yang optimal jangan mencoba untuk menutupi setiap kemungkinan melainkan alamat hanya komponen kunci, yang memungkinkan mereka untuk diselesaikan dalam waktu kurang dari 90 detik.

Beberapa praktisi berpendapat bahwa daftar periksa membuang waktu terlalu banyak; mereka gagal untuk menyadari bahwa jalan pintas untuk menghemat waktu sering en mengarah ke masalah kemudian, mengakibatkan kerugian bersih waktu. Jika daftar periksa keselamatan diikuti dalam setiap kasus, pengurangan tidak bisa signifi bisa dilihat dalam kejadian tions komplikasi bedah seperti bedah yang salah tempat, prosedur pada pasien yang salah, ditahan benda asing, dan kesalahan mudah dicegah lainnya. penyedia anestesi adalah pemimpin dalam inisiatif keselamatan pasien dan harus mengambil peran proaktif untuk memanfaatkan daftar periksa dan ikatan activi- lain yang menumbuhkan budaya keselamatan.

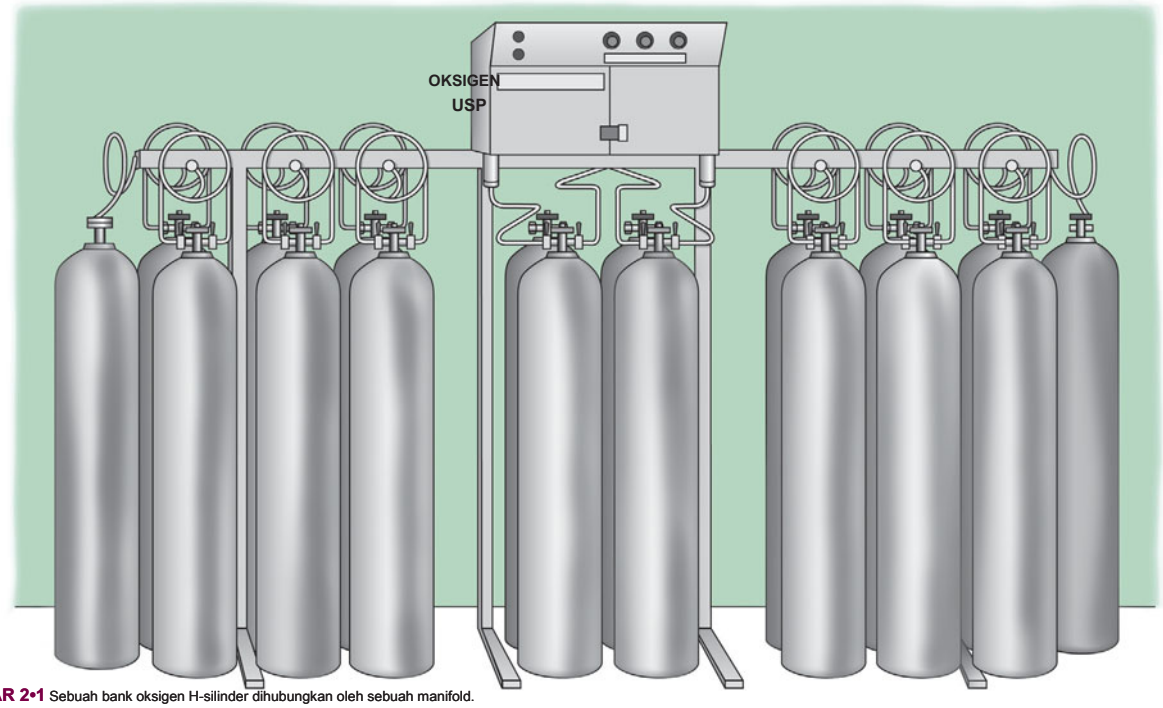
Sistem Gas Medis

Th e gas medis yang biasa digunakan dalam ruang operasi yang oksigen, nitrous oxide, udara, dan nitrogen. Meskipun secara teknis bukan gas, vakum buang untuk pembuangan limbah anestesi gas (WAGD atau pemulungan) dan hisap bedah juga harus disediakan dan dianggap sebagai bagian integral dari sistem gas medis. Pasien terancam punah jika sistem gas medis, par- oksigen ticularly, yang misconfi gured atau kerusakan. e fitur utama th sistem tersebut adalah sumber gas dan sarana pengiriman mereka ke ruang operasi. Th e ahli anestesi harus di bawah- berdiri kedua elemen ini untuk mencegah dan mendeteksi penipisan gas medis atau jalur suplai misconnection. Perkiraan permintaan puncak sebuah rumah sakit tertentu menentukan jenis sistem pasokan gas medis yang diperlukan.

SUMBER MEDICAL GAS

Oksigen

Sebuah pasokan oksigen merupakan kebutuhan penting dalam area bedah. kelas medis oksigen (99% atau 99,5% murni) yang diproduksi oleh tion distilla- pecahan dari liquefi ed udara. Oksigen disimpan sebagai terkompresi

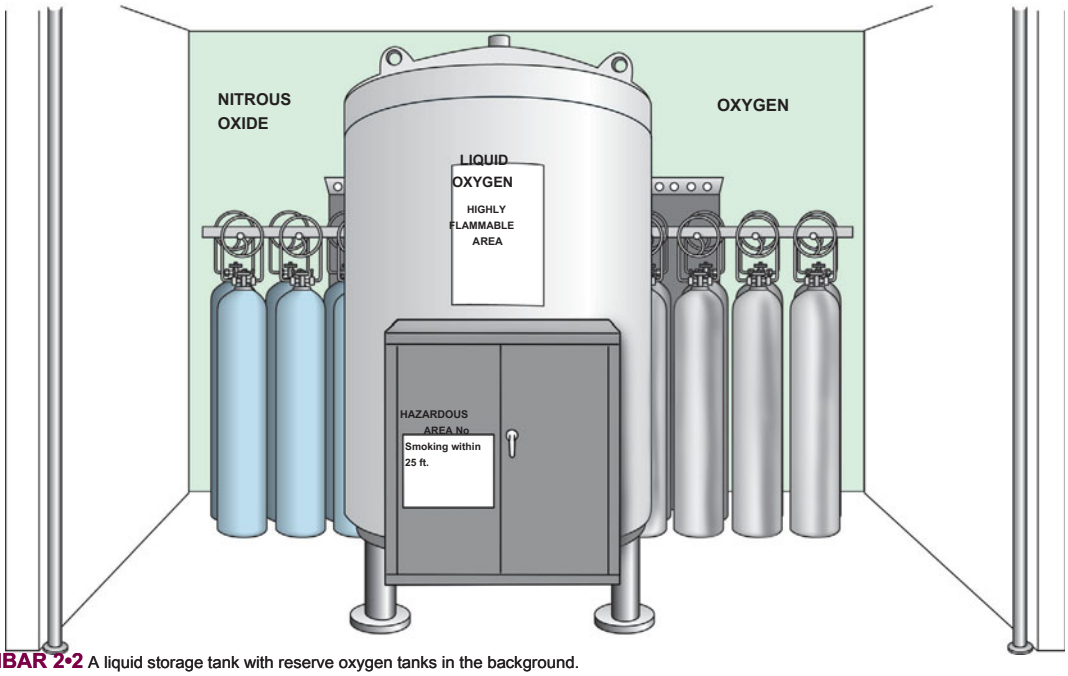


GAMBAR 2•1 Sebuah bank oksigen H-silinder dihubungkan oleh sebuah manifold.

gas pada suhu kamar atau didinginkan sebagai cairan. Sebagian besar rumah sakit kecil menyimpan oksigen dalam dua bank terpisah dari silinder tekanan tinggi (H-silinder) con nected oleh manifold (Gambar 2-1). Hanya satu bank digunakan pada suatu waktu. Th e jumlah silinder di masing-masing bank tergantung pada diantisipasi permintaan harian. Th e berjenis berisi katup yang mengurangi tekanan silinder (sekitar 2000 pound per inci persegi [psig]) tekanan line (55 ± 5 psig) dan berjalan otomatis matically beralih bank ketika satu kelompok silinder habis.

Sebuah sistem penyimpanan oksigen cair (Gambar 2-2) lebih ekonomis untuk rumah sakit besar. oksigen cair harus disimpan di bawah suhu kritis dari
- 119 ° C karena gas dapat liquefi ed oleh tekanan *hanya* jika disimpan di bawah suhu kritis mereka. Sebuah rumah sakit besar mungkin memiliki pasokan oksigen cair lebih kecil atau bank terkompresi tabung gas yang dapat memberikan kebutuhan oksigen satu hari sebagai cadangan. Untuk menjaga terhadap kegagalan gas-sistem rumah sakit, inti anesthesiolo- harus selalu memiliki darurat (E-silinder) lapis dukungan-oksigen yang tersedia selama anestesi.

Kebanyakan mesin anestesi mengakomodasi E-silinder oksigen (tabel 2-1). Seperti oksigen dikeluarkan, tekanan silinder jatuh dalam proporsi untuk isinya. Tekanan 1000 psig puncak-Cates E-silinder yang kira-kira setengah penuh dan mewakili 330 L oksigen pada tekanan atmosfer dan suhu 20 ° C. Jika oksigen habis pada tingkat 3 L / menit, silinder yang setengah penuh akan kosong di 110 menit. tekanan silinder oksigen harus dipantau sebelum digunakan dan secara periodik selama penggunaan. mesin anestesi biasanya juga mengakomodasi E-silinder untuk udara medis dan nitrous oxide, dan dapat menerima silinder helium. Compressed gas medis memanfaatkan pin sistem keamanan indeks silinder ini untuk mencegah Crossover sengaja dan koneksi untuk jenis gas diff erent. Sebagai fitur keselamatan oksigen E-silinder, kuk memiliki komponen yang tidak terpisahkan yang terbuat dari logam Wood. Th adalah paduan metalurgi memiliki titik leleh yang rendah, yang memungkinkan disipasi tekanan yang mungkin panas botol ke titik ledakan balistik. Th adalah pelepas tekanan “katup” adalah



GAMBAR 2•2 A liquid storage tank with reserve oxygen tanks in the background.

dirancang untuk pecah di 3300 psig, jauh di bawah dinding tekanan E-silinder harus dapat dengan- berdiri (lebih dari 5000 psig).

Oksida nitrat

oksida nitrat diproduksi oleh pemanasan ammo- nium nitrat (dekomposisi termal). Hal ini hampir selalu disimpan oleh rumah sakit di besar H-silinder con- nected oleh manifold dengan fitur crossover yang otomatis. penyimpanan cairan curah nitrous oksida eko nomical hanya di lembaga-lembaga yang sangat besar.

Karena suhu kritis nitrous oxide (36,5 ° C) di atas suhu kamar, dapat disimpan liquefi ed tanpa sistem timbangkan refrig- rumit . Jika liquefi ed naik nitrous oxide di atas suhu kritis, ia akan kembali ke fase gas nya. Karena nitrous oksida bukan merupakan gas ideal dan mudah kompresibel, mation transfor- ini menjadi fase gas tidak disertai dengan kenaikan besar dalam tekanan tangki. Meskipun demikian, seperti tabung oksigen, semua nitrous oxide E-silinder dilengkapi dengan kuk logam Wood untuk mencegah

TABLE 2•1 Characteristics of medical gas cylinders.

Gas	E-Cylinder Capacity [1] (L)	H-Cylinder Capacity [1] (L)	Pressure [1] (psig at 20°C)	Color (USA)	Color (International)	Form
O_2	625–700	6000–8000	1800–2200	Green	White	Gas
Air	625–700	6000–8000	1800–2200	Yellow	White and black	Gas
N_2O	1590	15,900	745	Blue	Blue	Liquid
N_2	625–700	6000–8000	1800–2200	Black	Black	Gas

[1] Depending on the manufacturer.

explosion under conditions of unexpectedly high gas pressure (eg, unintentional overfi lling), particu- larly during fi res.

Although a disruption in supply is usually not catastrophic, most anesthesia machines have reserve nitrous oxide E-cylinders. Because these smaller cyl- inders also contain nitrous oxide in its liquid state, the volume remaining in a cylinder is *not* propor- tional to cylinder pressure. By the time the liquid nitrous oxide is expended and the tank pressure begins to fall, only about 400 L of nitrous oxide remains. **If liquid nitrous oxide is kept at a con- stant temperature (20°C), it will vaporize at the same rate at which it is consumed and will main- tain a constant pressure (745 psig) until the liquid is exhausted .**

Th e only reliable way to determine residual volume of nitrous oxide is to weigh the cylin- der. For this reason, the tare weight (TW), or empty weight, of cylinders containing a liquefi ed com- pressed gas (eg, nitrous oxide) is oft en stamped on the shoulder of the cylinder. Th e pressure gauge of a nitrous oxide cylinder should not exceed 745 psig at 20°C. A higher reading implies gauge malfunction, tank overfi ll (liquid fi ll), or a cylinder containing a gas other than nitrous oxide.

Because energy is consumed in the conversion of a liquid to a gas (the latent heat of vaporization), the liquid nitrous oxide cools. Th e drop in tempera- ture results in a lower vapor pressure and lower cyl- inder pressure. Th e cooling is so pronounced at high fl ow rates that there is oft en frost on the tank, and pressure regulators may freeze.

Medical Air

Th e use of air is becoming more frequent in anesthe- siology as the popularity of nitrous oxide and unnec- essarily high concentrations of oxygen has declined. Cylinder air is medical grade and is obtained by blending oxygen and nitrogen. Dehumidifi ed but unsterile air is provided to the hospital pipeline system by compression pumps. Th e inlets of these pumps must be distant from vacuum exhaust vents and machinery to minimize contamination. Because the critical temperature of air is –140.6°C, it exists as a gas in cylinders whose pressures fall in proportion to their content.

Nitrogen

Although compressed nitrogen is not administered to patients, it may be used to drive some operating room equipment, such as saws, drills, and surgical handpieces. Nitrogen supply systems either incorpo- rate the use of H-cylinders connected by a manifold or a wall system supplied by a compressor driven central supply.

Vacuum

A central hospital vacuum system usually consists of independent suction pumps, each capable of han- dling peak requirements. Traps at every user location prevent contamination of the system with foreign matter. Th e medical-surgical vacuum may be used for waste anesthetic gas disposal (WAGD) provid- ing it does not aff ect the performance of the system. Medical vacuum receptacles are usually black in color with white lettering. A dedicated WAGD vacuum system is generally required with modern anesthesia machines. Th e WAGD outlet may incorporate the use of a suction regulator with a fl oat indicator. Th e fl oat should be maintained between the designated markings. Excess suction may result in inadequate patient ventilation, and insuffi cient suction levels may result in the failure to evaluate WAGD. WAGD receptacles and tubing are usually lavender in color.

Carbon Dioxide

Many surgical procedures are performed using lapa- roscopic or robotic-assisted techniques requiring insuffl ation of body cavities with carbon dioxide, an odorless, colorless, nonfl ammable and slightly acidic gas. Large cylinders containing carbon dioxide, such as M-cylinders or LK-cylinders, are frequently found in the operating room; these cylinders share a common size orifi ce and thread with oxygen cylin- ders and can be inadvertently interchanged.

DELIVERY OF MEDICAL GASES

Medical gases are delivered from their central sup- ply source to the operating room through a piping network. Pipes are sized such that the pressure drop across the whole system never exceeds 5 psig. Gas pipes are usually constructed of seamless copper tubing using a special welding technique. Internal

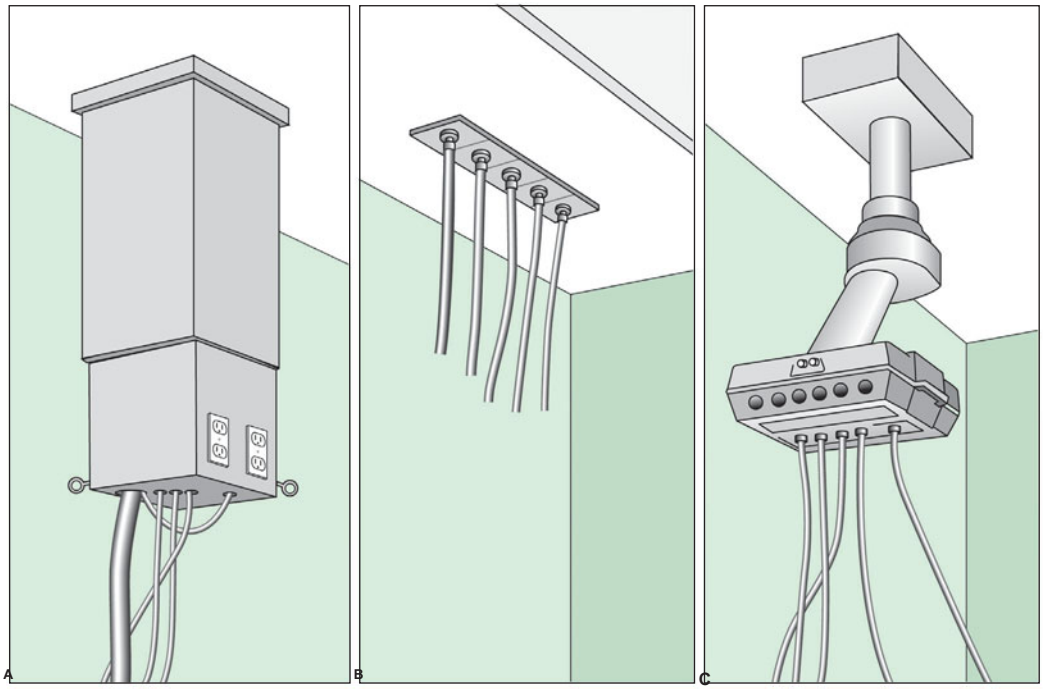


FIGURE 2•3 Typical examples of (A) gas columns, (B) ceiling hose drops, and (C) articulating arms. One end of a color-coded hose connects to the hospital medical gas supply system by way of a quick-coupler mechanism. The other end connects to the anesthesia machine through the diameter index safety system.

contamination of the pipelines with dust, grease, or water must be avoided. Th e hospital's gas deliv- ery system appears in the operating room as hose drops, gas columns, or elaborate articulating arms (Figure 2–3). Operating room equipment, including the anesthesia machine, interfaces with these pipe- line system outlets by color-coded hoses. Quick- coupler mechanisms, which vary in design with diff erent manufacturers, connect one end of the hose to the appropriate gas outlet. Th e other end connects to the anesthesia machine through a non- interchangeable diameter index safety system fi tting that prevents incorrect hose attachment.

E-cylinders of oxygen, nitrous oxide, and air attach directly to the anesthesia machine. To discourage incorrect cylinder attachments, cyl- inder manufacturers have adopted a pin index safety system. Each gas cylinder (sizes A–E) has two holes in its cylinder valve that mate with corresponding pins in the yoke of the anesthesia machine (Figure 2–4). Th e relative positioning of the pins and holes is unique for each gas. Multiple washers placed between the cylinder and yoke, which prevent proper engagement of the pins and holes, have unintention- ally defeated this system. Th e pin index safety system is also ineff ective if yoke pins are damaged or the cyl- inder is fi lled with the wrong gas.

Th e functioning of medical gas supply sources and pipeline systems is constantly monitored by central and area alarm systems. Indicator lights and audible signals warn of changeover to secondary gas sources and abnormally high (eg, pressure regulator malfunction) or low (eg, supply depletion) pipeline pressures (Figure 2–5).

Modern anesthesia machines and anesthetic gas analyzers continuously measure the fraction of inspired oxygen (Fi O_2). Analyzers have a variable threshold setting for the minimal Fi O_2 but should

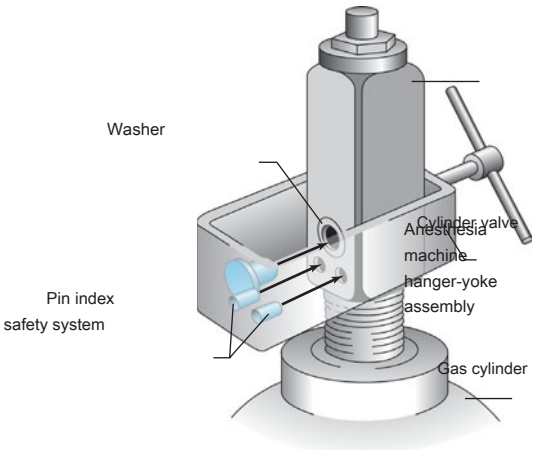


FIGURE 2•4 Pin index safety system interlink between the anesthesia machine and gas cylinder.

be confi gured to prevent disabling this alarm. Th e monitoring of Fi O_2 does not refl ect the oxygen con- centration distal to the monitoring port and should not be used to reference the oxygen concentration within devices such as endotracheal tubes or at the distal tip of the tube. Due to gas exchange, fl ow rates, and shunting a marked diff erence can exist between the monitored Fi O_2 and oxygen concentration at the tissue level.

Environmental Factors in the Operating Room

TEMPERATURE

Th e temperature in most operating rooms seems uncomfortably cold to many conscious patients and, at times, to anesthesiologists. However, scrub nurses and surgeons stand in surgical garb for hours under hot operating room lights. As a general principle, the comfort of operating room personnel must be reconciled with patient care. Hypothermia has been associated with an increased incidence of wound infection, greater intraoperative blood loss (impaired coagulation assessed by thromboelastography), and prolonged hospitalization (see Chapter 52).

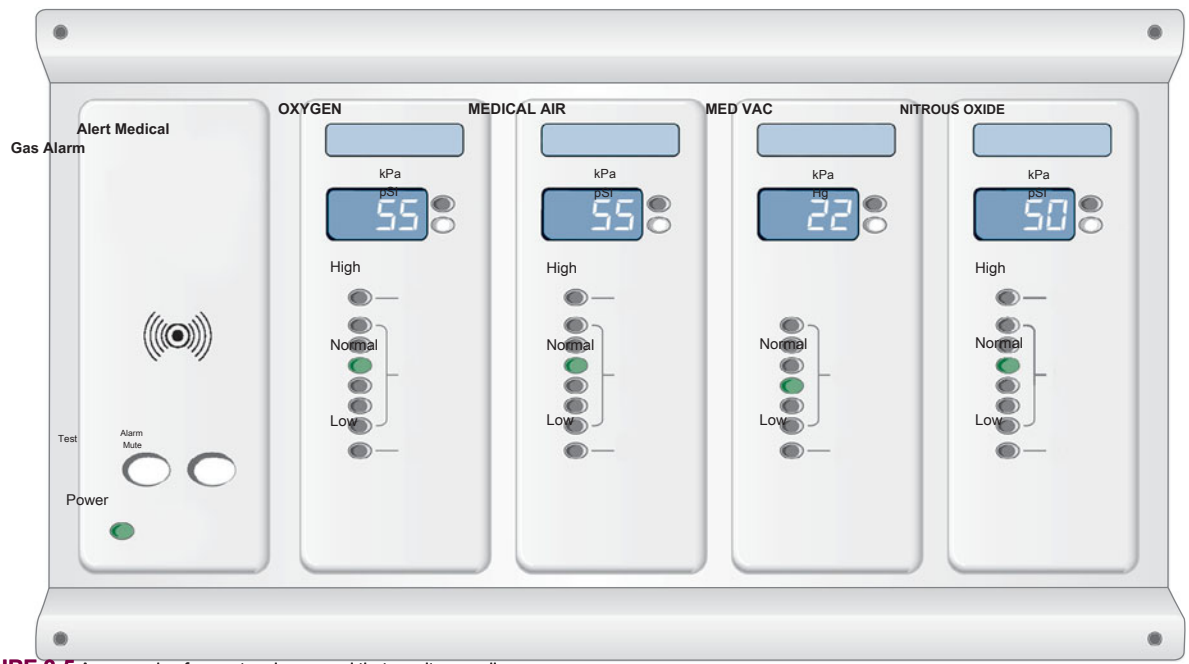


FIGURE 2•5 An example of a master alarm panel that monitors gasline pressure.

HUMIDITY

In past decades, static discharges were a feared source of ignition in an operating room fi lled with fl ammable anesthetic vapors. Now humidity con- trol is more relevant to infection control practices. Optimally humidity levels in the operating room should be maintained between 50% and 55%. Below this range the dry air facilitates airborne motil- ity of particulate matter, which can be a vector for infection. At high humidity, dampness can aff ect the integrity of barrier devices such as sterile cloth drapes and pan liners.

VENTILATION

A high rate of operating room airfl ow decreases contamination of the surgical site. Th ese fl ow rates, usually achieved by blending up to 80% recircu- lated air with fresh air, are engineered in a manner to decrease turbulent fl ow and be unidirectional. Although recirculation conserves energy costs associated with heating and air conditioning, it is unsuitable for WAGD. Th erefore, a separate anes- thetic gas scavenging system must always supple- ment operating room ventilation. Th e operating room should maintain a slightly positive pressure to drive away gases that escape scavenging and should be designed so fresh air is introduced through or near the ceiling and air return is handled at or near fl oor level. Ventilation considerations must address air quality and volume changes. Th e National Fire Protection Agency (NFPA) recommends 25 air vol- ume exchanges per hour to decrease risk of stag- nation and bacterial growth. Air quality should be maintained by adequate air fi ltration using a 90% fi lter, defi ned simply as one that fi lters out 90% of particles presented. High-effi ciency par- ticulate fi lters (HEPA) are frequently used but are not required by engineering or infection control standards.

NOISE

Multiple studies have demonstrated that expo- sure to noise can have a detrimental eff ect on mul- tiple human cognitive functions and may result in hearing impairment with prolonged exposure.

Operating room noise has been measured at 70–80 decibels (dB) with frequent sound peaks exceeding 80 dB. As a reference, if your speaking voice has to be raised above conversational level, then ambient noise is approximated at 80 dB. Noise levels in the operating room approach the time-weighted aver- age (TWA) for which the Occupational Safety and Health Administration (OSHA) requires hearing protection. Orthopedic air chisels and neurosurgical drills can approach the noise levels of 125 dB, the level at which most human subjects begin to experi- ence pain.

IONIZING RADIATION

Radiation is an energy form that is found in spe- cifi c beams. For the anesthesia provider radiation is usually a component of either diagnostic imaging or radiation therapy. Examples include fl uoroscopy, linear accelerators, computed tomography, directed beam therapy, proton therapy, and diagnostic radiographs. Human eff ects of radiation are mea- sured by units of absorbed doses such as the gray (Gy) and rads or equivalent dose units such as the Sievert (Sv) and Roentgen equivalent in man (REM). Radiation-sensitive organs such as eyes, thyroid, and gonads must be protected, as well as blood, bone marrow, and fetus. Radiation levels must be monitored if individuals are exposed to greater than 40 REM. Th e most common method of measurement is by fi lm badge. Lifetime exposure can be tabulated by a required database of fi lm badge wearers.

A basic principle of radiation safety is to keep exposure "as low as reasonably practical" (ALARP). Th e principles of ALARP are protection from radiation exposure by the use of time, dis- tance, and shielding. Th e length of time of exposure is usually not an issue for simple radiographs such as chest fi lms but can be signifi cant in fl uoroscopic procedures such as those commonly performed during interventional radiology, c-arm use, and in the diagnostic gastroenterology lab. Exposure can be reduced to the provider by increasing the dis- tance between the beam and the provider. Radiation exposure over distance follows the inverse square law. To illustrate, intensity is represented as $1/d_2$

(where *d* = distance) so that 100 mRADs at 1 inch will be 0.01 mRADs at 100 inches. Shielding is the most reliable form of radiation protection; typical personal shielding is in the form of leaded apron and glasses. Physical shields are usually incorporated into radiological suites and can be as simple as a wall to stand behind or a rolling leaded shield to place between the beam and the provider. Although most modern facilities are designed in a very safe manner, providers can still be exposed to scattered radiation as atomic particles are bounced off shielding. For this reason radiation protection should be donned whenever ionizing radiation is used.

As use of reliable shielding has increased, the incidence of radiation-associated diseases of sen- sitive organs has decreased, with the exception of radiation-induced cataracts. Because protec- tive eyewear has not been consistently used to the same degree as other types of personal protection, radiation-induced cataracts are increasing among employees working in interventional radiology suites. Anesthesia providers who work in these environments should consider the use of leaded goggles or glasses to decrease the risk of such problems.

Electrical Safety

THE RISK OF ELECTROCUTION

Th e use of electronic medical equipment subjects patients and hospital personnel to the risk of elec- trocution. Anesthesiologists must have at least a basic understanding of electrical hazards and their prevention.

Body contact with two conductive materials at diff erent voltage potentials may complete a cir- cuit and result in an electrical shock. Usually, one point of exposure is a live 110-V or 240-V conduc- tor, with the circuit completed through a ground contact. For example, a grounded person need con- tact only one live conductor to complete a circuit and receive a shock. Th e live conductor could be the frame of a patient monitor that has developed a fault to the hot side of the power line. A circuit is now complete between the power line (which is earth grounded at the utility company's pole-top transformer) through the victim and back to the ground (**Figure 2–6**). Th e physiological eff ect of electrical current depends on the location, dura- tion, frequency, and magnitude (more accurately, current density) of the shock.

Leakage current is present in all electrical equipment as a result of capacitive coupling, induc- tion between internal electrical components, or defective insulation. Current can fl ow as a result of capacitive coupling between two conductive bod- ies (eg, a circuit board and its casing) even though they are not physically connected. Some monitors are doubly insulated to decrease the eff ect of capac- itive coupling. Other monitors are designed to be connected to a low-impedance ground (the safety ground wire) that should divert the current away from a person touching the instrument's case.

Th e magnitude of such leaks is normally imperceptible to touch (<1 mA, and well below the fi brillation threshold of 100 mA). If the current bypasses the high resistance off ered by skin, however, and is applied **directly to the heart (microshock), current as low as 100 μ A** may be fatal. Th e maximum leakage allowed in operating **room equipment is 10 μ A.**

Cardiac pacing wires and invasive monitor- ing catheters provide a conductive pathway to the myocardium. In fact, blood and normal saline can serve as electrical conductors. Th e exact amount of current required to produce fi brillation depends on the timing of the shock relative to the vulner- able period of heart repolarization (the T wave on the electrocardiogram). Even small diff erences in potential between the earth connections of two electrical outlets in the same operating room might place a patient at risk for microelectrocution.

PROTECTION FROM ELECTRICAL SHOCK

Most patient electrocutions are caused by cur- rent fl ow from the live conductor of a grounded circuit through the body and back to a ground (Figure 2–6). Th is would be prevented if everything in the operating room were grounded except the patient. Although direct patient grounds should be avoided, complete patient isolation is not feasible

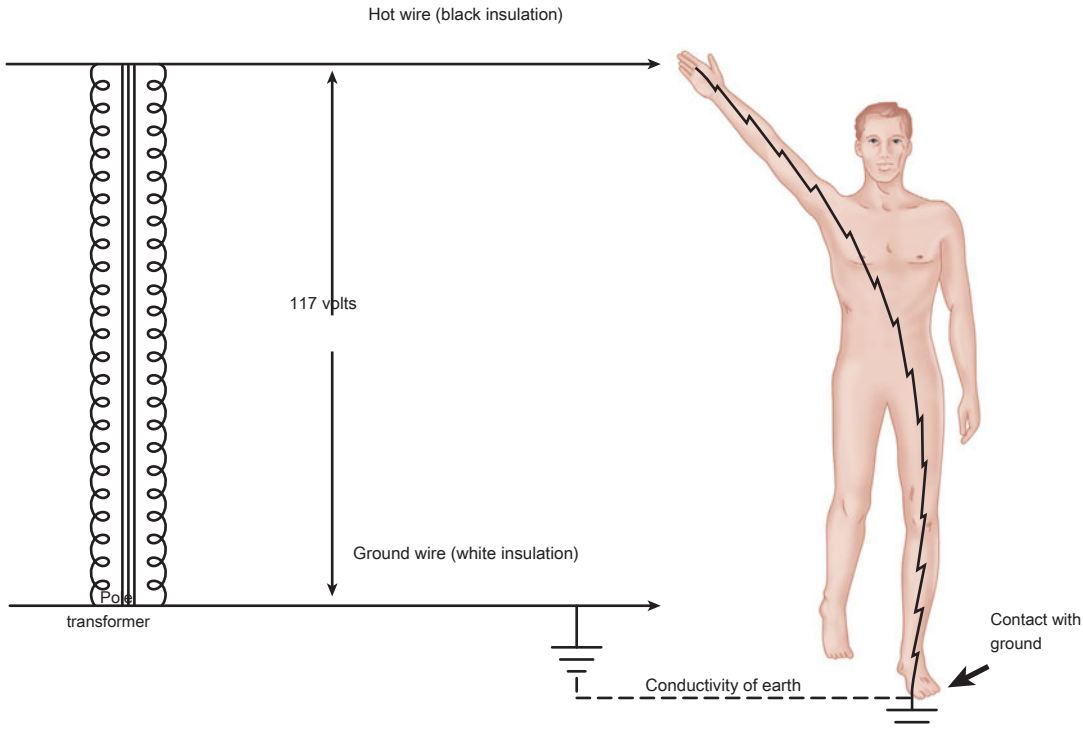


FIGURE 2•6 The setting for the great majority of electric shocks. An accidentally grounded person simultaneously contacts the hot wire of the electric service, usually via defective equipment that provides a pathway linking the hot wire to an exposed conductive surface. The complete electrical loop originates with the secondary of the pole transformer (the voltage source) and extends through the hot wire, the victim and the victim's contact with a ground, the earth itself, the neutral ground rod at the service entrance, and back to the transformer via the neutral (or ground) wire. (Modifi ed and reproduced, with permission, from Bruner J, Leonard PF: *Electricity, Safety, and the Patient* . Mosby Year Book, 1989.)

during surgery. Instead, the operating room power supply can be isolated from grounds by an **isolation transformer (Figure 2–7).**

Unlike the utility company's pole-top trans- former, the secondary wiring of an isolation trans- former is not grounded and provides two live ungrounded voltage lines for operating room equip- ment. Equipment casing—but not the electrical circuits—is grounded through the longest blade of a three-pronged plug (the safety ground). If a live wire is then unintentionally contacted by a grounded patient, current will not fl ow through the patient since no circuit back to the secondary coil has been completed (**Figure 2–8**).

Of course, if both power lines are contacted, a circuit is completed and a shock is possible. In addition, if either power line comes into contact with a ground through a fault, contact with the other power line will complete a circuit through a grounded patient. To reduce the chance of two coexisting faults, a **line isolation moni- tor** measures the potential for current fl ow from the isolated power supply to the ground (**Figure 2–9**). Basically, the line isolation monitor determines the degree of isolation between the two power wires and the ground and predicts the amount of current that *could* fl ow if a second short circuit were to develop. An alarm is activated if an unacceptably high current fl ow to the ground becomes possible (usually 2 mA or 5 mA), but power is not interrupted unless a ground-fault cir- cuit interrupter is also activated. Th e latter, a fea- ture of household bathrooms, is usually not installed in locations such as operating rooms,

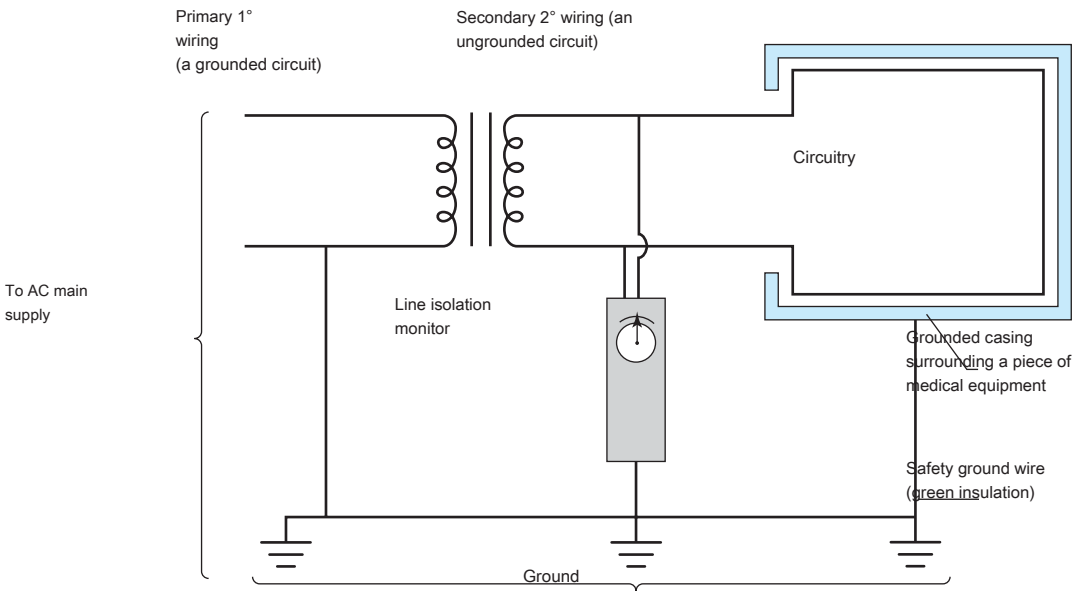


FIGURE 2•7 A circuit diagram of an isolation transformer and monitor.

where discontinuation of life support systems (eg, cardiopulmonary bypass machine) is more hazard- ous than the risk of electrical shock. Th e alarm of the line isolation monitor merely indicates that the power supply has partially reverted to a grounded system. In other words, while the line isolation monitor warns of the existence of a single fault (between a power line and a ground), two faults are required for a shock to occur. Since the line isola- tion monitor alarms when the sum of leakage cur- rent exceeds the set threshold, the last piece of equipment is usually the defective one; however, if this item is life-sustaining, other equipment can be removed from the circuit to evaluate whether the life safety item is truly at fault.

Even isolated power circuits do not provide complete protection from the small currents capable of causing microshock fi brillation. Furthermore, the line isolation monitor cannot detect all faults, such as a broken safety ground wire within a piece of equipment. Despite the overall utility of isolated power systems, they add to construction costs. Th eir requirement in operating rooms was deleted from the National Electrical Code in 1984, and circuits of newer or remodeled operating rooms may off er less protection from electroshock injury than circuits of a household bathroom.

Th ere are, however, modern equipment designs that decrease the possibility of microelectrocu- tion. Th ese include double insulation of the chas- sis and casing, ungrounded battery power supplies, and patient isolation from equipment-connected grounds by using optical coupling or transformers.

SURGICAL DIATHERMY

Electrosurgical units (ESUs) generate an ultra- high-frequency electrical current that passes from a small active electrode (the cautery tip) through the patient and exits by way of a large plate elec- trode (the dispersal pad, or return electrode). Th e high current density at the cautery tip is capable of tissue coagulation or cutting, depending on the electrical waveform. Ventricular fi brillation is pre- vented by the use of ultrahigh electrical frequencies (0.1–3 MHz) compared with line power (50–60 Hz). Th e large surface area of the low-impedance return electrode avoids burns at the current's point of exit by providing a low current density (the con- cept of *exit* is technically incorrect, as the current

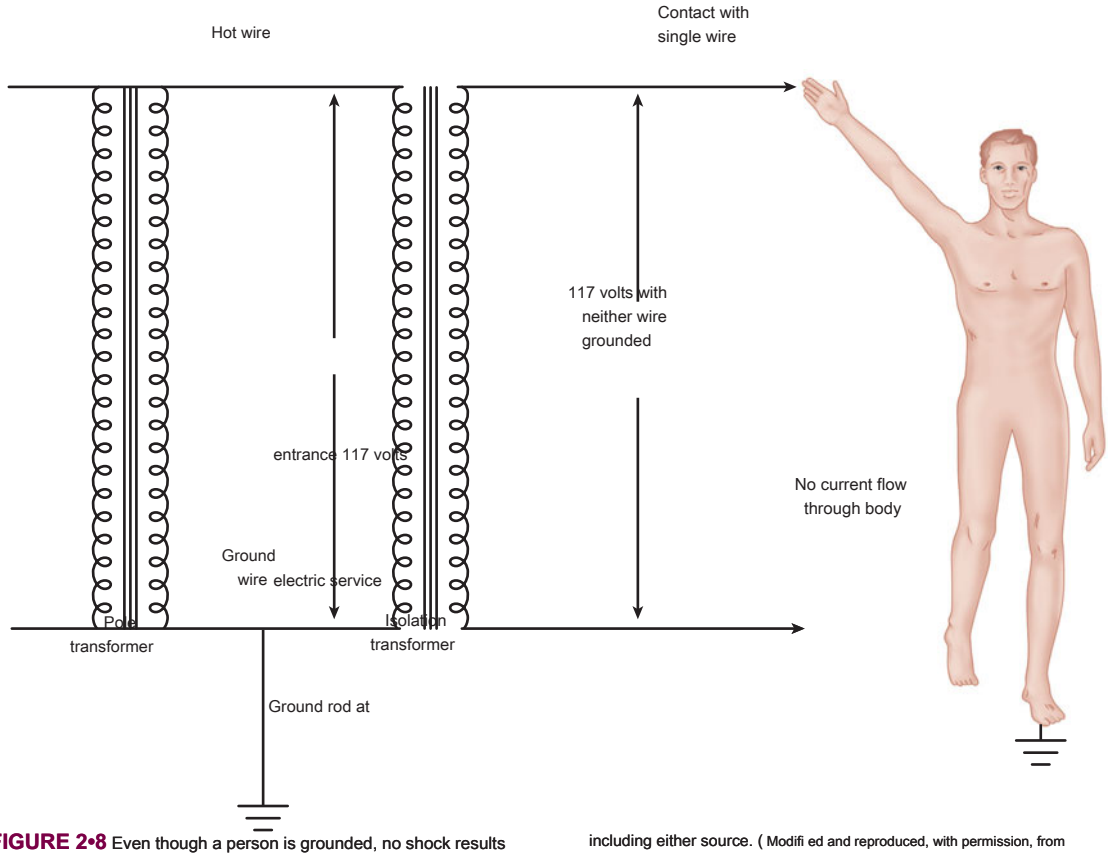


FIGURE 2•8 Even though a person is grounded, no shock results from contact with one wire of an isolated circuit. The individual is in simultaneous contact with two separate voltage sources but does not close a loop including either source. (Modifi ed and reproduced, with permission, from Bruner J, Leonard PF: *Electricity, Safety, and the Patient* . Mosby Year Book, 1989.)

is alternating rather than direct). Th e high power levels of ESUs (up to 400 W) can cause inductive coupling with monitor cables, leading to electrical interference.

Malfunction of the dispersal pad may result from disconnection from the ESU, inadequate patient contact, or insuffi cient conductive gel. In these situations, the current will fi nd another place to exit (eg, electrocardiogram pads or metal parts of the operating table), which may result in a burn (Figure 2–10). Precautions to prevent diathermy burns include proper return electrode placement, avoiding prostheses and bony protuberances, and elimination of patient-to-ground contacts. Current fl ow through the heart may lead to dysfunction of an implanted cardiac rhythm management device (CRMD). Th is can be minimized by placing the return electrode as close to the surgical fi eld and as far from the CRMD as practical.

Newer ESUs are isolated from grounds using the same principles as the isolated power supply (isolated output versus ground-referenced units). Because this second layer of protection provides ESUs with their own isolated power supply, the oper- ating room's line isolation monitor may not detect an electrical fault. Although some ESUs are capable of detecting poor contact between the return elec- trode and the patient by monitoring impedance, many older units trigger the alarm only if the return electrode is unplugged from the machine. Bipolar

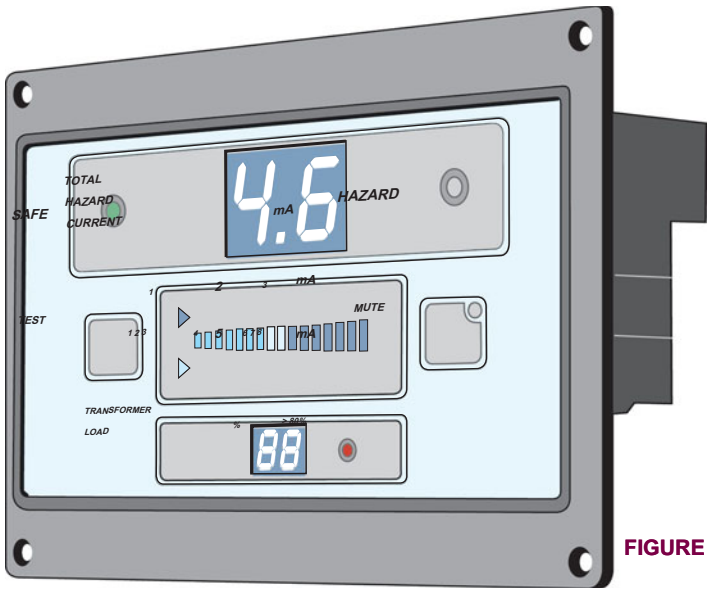


FIGURE 2•9 A line isolation monitor.

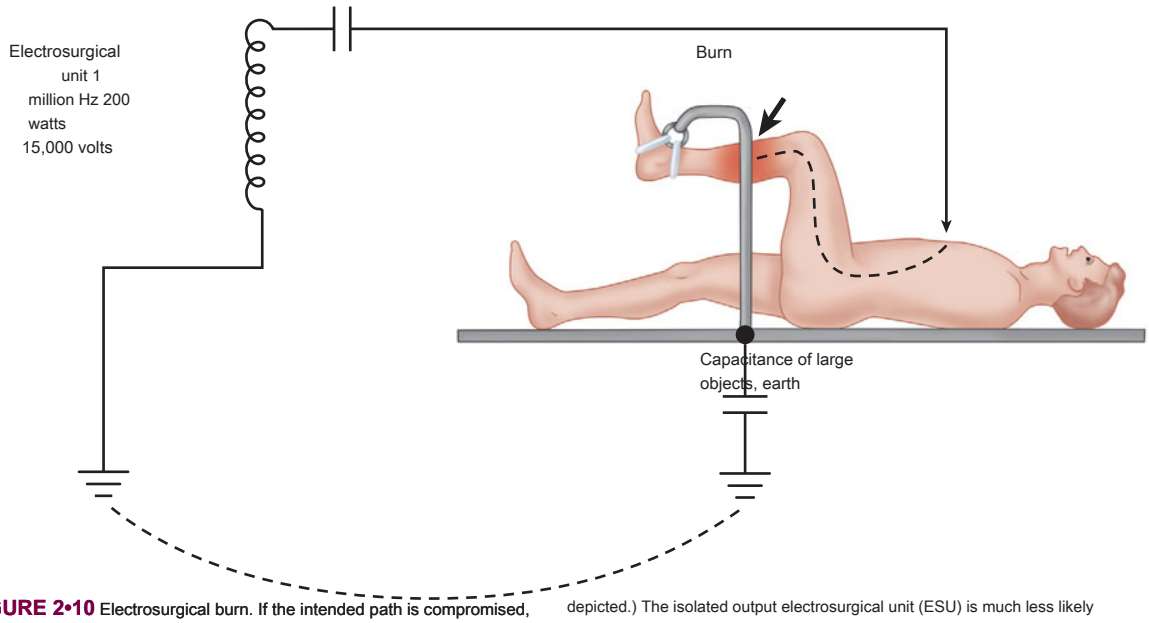


FIGURE 2•10 Electrosurgical burn. If the intended path is compromised, the circuit may be completed through other routes. Because the current is of high frequency, recognized conductors are not essential; capacitances can complete gaps in the circuit. Current passing through the patient to a contact of small area may produce a burn. (A leg drape would not off er protection in the situation depicted.) The isolated output electrosurgical unit (ESU) is much less likely than the ground-referenced ESU to provoke burns at ectopic sites. *Ground-referenced* in this context applies to the ESU output and has nothing to do with isolated versus grounded power systems. (Modifi ed and reproduced, with permission, from Bruner J, Leonard PF: *Electricity, Safety, and the Patient* . Mosby Year Book, 1989.)

electrodes confi ne current propagation to a few mil- limeters, eliminating the need for a return electrode. Because pacemaker and electrocardiogram inter- ference is possible, pulse or heart sounds should be closely monitored when any ESU is used. Automatic implanted cardioversion and defi brillator devices may need to be suspended if monopolar ESU is used and any implanted CRMD should be interrogated aft er use of a monopolar ESU.

Surgical Fires & Thermal Injury

FIRE PREVENTION & PREPARATION

Surgical fi res are relatively rare, with an incidence of about 1:87,000 cases, which is close to the inci- dence rate of other events such as retained for- eign objects aft er surgery and wrong-site surgery.

Almost all surgical fi res can be prevented. Unlike medical complications, fi res are a product of simple physical and chemical proper- ties. Occurrence is guaranteed given the proper combination of factors but can be eliminated almost entirely by understanding the basic princi-

ples of fi re risk. Likely the most common risk factor for surgical fi re relates to the open delivery of oxygen.

Situations classifi ed as carrying a high risk for a surgical fi re are those that involve an ignition source used in close proximity to an oxidizer. Th e simple chemical combination required for any fi re is com- monly referred to as the fi re triad or fi re triangle. Th e triad is composed of fuel, oxidizer, and ignition source (heat). Table 2–2 lists potential contributors to fi res and explosions in the operating room. Surgical fi res can be managed and possibly avoided completely by incorporating education, fi re drills, preparation, prevention, and response into educational programs provided to operating room personnel.

TABLE 2•2 Potential contributors to operating room fi res and explosions.

Flammable agents (fuels)	Solutions, aerosols, and ointments Alcohol Chlorhexidine Benzoin Mastisol Acetone Petroleum products Surgical drapes (paper and cloth) Surgical gowns Surgical sponges and packs Surgical sutures and mesh Plastic/polyvinyl chloride/latex products Endotracheal tubes Masks Cannulas Tubing Intestinal gases Hair
Gases supporting combustion (oxidizers)	Oxygen Nitrous oxide
Ignition sources (heat)	Lasers Electrosurgical units Fiberoptic light sources (distal tip) Drills and burrs External defi brillators

For anesthesia providers, fi re prevention edu- cation should place a heavy emphasis on the risk relating to the open delivery of oxygen. Th e Anes- thesia Patient Safety Foundation has developed an educational video and online teaching module that provides fi re safety education from the perspective of the anesthesia provider.

Operating room fi re drills increase awareness of the fi re hazards associated with surgical procedures. In contrast to the typical institutional fi re drill, these drills should be specifi c to the operating room and should place a greater emphasis on the particular risks associated with that setting. For example, consideration should be given to both vertical and hori- zontal evacuation of surgical patients, movement of patients requiring ventilatory assistance, and unique situations such as prone or lateral positioning and movement of patients who may be fi xed in neuro- surgical pins.

Preparation for surgical fi res can be incorpo- rated into the time-out process of the universal protocol. Team members should be introduced and specifi c roles agreed upon should a fi re erupt. Items needed to properly manage a fi re can be assembled

or identifi ed beforehand (eg, ensuring the proper endotracheal tube for patients undergoing laser surgery; having water or saline ready on the surgi- cal fi eld; identifying the location of fi re extinguish- ers, gas cutoff valves, and escape routes). A poster or fl owsheet to standardize the preparation may be of benefi t.

Preventing catastrophic fi res in the operating room begins with a strong level of communication among all members of the surgical team. Diff erent aspects of the fi re triad are typically under the domain of particular surgical team members. Fuels such as alcohol-based solutions, adhesive removers, and surgical drapes and towels are typically con- trolled by the circulating nurse. Ignition sources such as electrocautery, lasers, drills, burrs, and light sources for headlamps and laparoscopes are usually controlled by the surgeon. Th e anesthesia provider maintains control of the oxidizer concentration of oxygen and nitrous oxide. Communication between personnel is evident when a surgeon enters the air- way and verifi es the concentration of oxygen before using cautery, or when an anesthesiologist asks the circulator to confi gure drapes to prevent the accu- mulation of oxygen in a surgical case that involves sedation and use of a nasal cannula.

Administration of oxygen in concentrations of greater than 30% should be guided by clinical presentation of the patient and not solely by proto- cols or habits. If oxygen is being delivered via nasal cannula or face mask, and if increased oxygen lev- els are needed, then the airway should be secured by either endotracheal tube or supraglottic device. Th is is of prime importance when the surgical site is above the level of the xiphoid.

When the surgical site is in or near the airway and a fl ammable tube is present, the oxygen concen- tration should be reduced for a suffi cient period of time before use of an ignition device (eg, laser or cautery) to allow reduction of oxygen concentration at the site. Laser airway surgery should incorporate either jet ventilation without an endotracheal tube or the appropriate protective tube specifi c for the wavelength of the laser. Precautions for laser cases are outlined below.

Alcohol-based skin preparations are extremely fl ammable and require an adequate drying time. Pooling of solutions must be avoided. Large pre- fi lled swabs of alcohol-based solution should be used with caution on the head or neck to avoid both oversaturation of the product and excess fl ammable waste. Product inserts are a good source of infor- mation about these preparations. Surgical gauze and sponges should be moistened with sterile water or saline if used in close proximity to an ignition source.

Should a fi re occur in the operating room it is important to determine whether the fi re is located *on the patient, in the airway,* or *elsewhere in the operating room* . For fi res occurring in the airway, the delivery of fresh gases to the patient must be stopped. Eff ective means of stopping fresh gases to the patient can be accomplished by turning off fl owmeters, disconnecting the circuit from the machine, or disconnecting the circuit from the endotracheal tube. Th e endotracheal tube should be removed and either sterile water or saline should be poured into the airway to extinguish any burning embers. Th e sequence of stopping gas fl ow and removal of the endotracheal tube when fi re occurs in the airway is not as important as ensuring that both actions are performed quickly. Oft en the two tasks can be accomplished at the same time and even by the same individual. If car- ried out by diff erent team members, the personnel should act without waiting for a predetermined sequence of events. Aft er these actions are carried out, ventilation may be resumed, preferably using room air and avoiding oxygen or nitrous oxide– enriched gases. Th e tube should be examined for missing pieces. Th e airway should be reestablished and, if indicated, examined with a bronchoscope. Treatment for smoke inhalation and possible trans- fer to a burn center should also be considered.

For fi res on the patient, the fl ow of oxidizing gases should be stopped, the surgical drapes removed, and the fi re extinguished by water or smothering. Th e patient should be assessed for injury. If the fi re is not immediately extinguished by fi rst attempts, then a carbon dioxide (CO_2) fi re extinguisher may be used. Further actions may include evacuation of the patient and activation of the nearest pull station. As noted previously, prior to an actual emergency, the location of fi re extinguishers, emergency exits,

and fresh gas cutoff valves should be established by the anesthesia provider.

Fires that result in injuries requiring medi- cal treatment or death must be reported to the fi re marshal, who retains jurisdiction over the facility. Providers should gain basic familiarity with local reporting standards, which can vary according to location.

Cases in which supplemental delivery of oxy- gen is used and the surgical site is above the xiphoid constitute the most commonly reported scenario for surgical fi res. Frequently the face or airway is involved, resulting in life-threatening injuries and the potential for severe facial disfi gurement. For the most part, these fi res can be avoided by the elimi- nation of the open delivery of oxygen, by use of an oxygen blender, or by securing the airway.

FIRE EXTINGUISHERS

For fi res not suppressed by initial attempts or those in which evacuation may be hindered by the location or intensity of the fi re, the use of a por- table fi re extinguisher is warranted. A CO_2 extin- guisher should be safe during external and internal exposure for fi res on the patient in the operating room. CO_2 readily dissipates, is not toxic, and as used in an actual fi re is not likely to result in thermal injury. FE-36, manufactured by DuPont, also can be used to extinguish fi res but is expen- sive. Both choices are equally eff ective and accept- able agents as refl ected by manufacturers' product information.

"A"-rated extinguishers contain water, which makes their use in the operating room problem- atic because of the presence of so much electrical equipment. A water mist "AC"-rated extinguisher is excellent but requires time and an adequate volume of mist over multiple attempts to extinguish the fi re. Furthermore, these devices are large and dif- fi cult to maneuver. Both can be made cheaply in a nonferromagnetic extinguisher, making them the best choice for fi res involving magnetic resonance imagers. Halon extinguishers, although very eff ec- tive, are being phased out because of concerns about depletion of the ozone layer, as well as the hypoxic atmosphere that results for rescuers. Halotrons are "greener" halon-type extinguishers that may have fewer eff ects on the ozone layer.

LASER SAFETY

Lasers are commonly used in operating rooms and procedure areas. When lasers are used for airway surgeries or for procedures involving the neck and face, the case should be considered as high risk for surgical fi re and managed as previously discussed. Th e type of laser (CO_2, neodymium yttrium alumi- num garnet [NG:YAG], or potassium titanyl phos- phate [KTP]), wavelength, and focal length are all important considerations for the safe operation of medical lasers. Without this vital information, oper- ating room personnel cannot adequately protect

themselves or the patient from harm. Before beginning laser surgery, the laser device should be in the operating room, warning signs should be posted on the doors, and protective eyewear should be issued. Th e anesthesia provider should ensure that the warning signs and eyewear match the label- ing on the device as protection is specifi c to the type of laser. Th e American National Standards Institute (ANSI) standards specify that eyewear and laser devices must be labeled for the wavelength emitted or protection off ered. Some ophthalmologic lasers and vascular mapping lasers have such a short focal length that protective eyewear is not needed. For other devices, protective goggles should be worn by personnel at all times during laser use, and eye pro- tection in the form of either goggles or protective eye patches should be used on the patient.

Laser endotracheal tube selection should be based on laser type and wavelength. Th e product insert and labeling for each type of tube should be compared to the type of laser used. Certain tech- nical limitations are present when selecting laser tubes. For instance, tubes less than 4.0 mm in diam- eter are not compatible with the ND:YAG or argon laser nor are ND:YAG-compatible tubes available in half sizes. Attempts to wrap conventional endotra- cheal tubes with foil should be avoided. Th is archaic method is not approved by either manufacturers or the U.S. Food and Drug Administration, is prone to breaking or unraveling, and does not confer pro- tection against laser penetration. Alternatively, jet

ventilation without an endotracheal tube can off er a reduced risk of airway fi re.

CREW RESOURCE MANAGEMENT: CREATING A CULTURE OF SAFETY IN THE OPERATING ROOM

Crew resource management (CRM) was developed in the aviation industry to allow personnel to inter- vene or call for investigation of any situation thought to be unsafe. Comprising seven principles, its goal is to avoid errors caused by human actions. In the air- line model CRM gives any crew member the author- ity to question situations that fall outside the range of normal practice. Before the implementation of CRM, crew members other that the captain had little or no input on aircraft operations. Aft er CRM was instituted, anyone identifying a safety issue could take steps to ensure adequate resolution of the situation. Th e ben- efi t of this method in the operating room is clear, given the potential for a deadly mistake to be made.

Th e seven principles of CRM are (1) adaptabil- ity/fl exibility, (2) assertiveness, (3) communication, (4) decision making, (5) leadership, (6) analysis, and (7) situational awareness. *Adaptability/fl exibility* refers to the ability to alter a course of action when new information becomes available. For example, if a major blood vessel is unintentionally cut in a routine procedure, the anesthesiologist must recog- nize that the anesthetic plan has changed and vol- ume resuscitation must be made even in presence of medical conditions that typically contraindicate large-volume fl uid administration.

Assertiveness is the willingness and readiness to actively participate, state, and maintain a position until convinced by the facts that other options are better; this requires the initiative and the courage to act. For instance, if a senior and well-respected sur- geon tells the anesthesiologist that the patient's aor- tic stenosis is not a problem because it is a chronic condition and the procedure will be relatively quick, the anesthesiologist should respond by voicing con- cerns about the management of the patient and should not proceed until a safe anesthetic and surgi- cal plan have been agreed upon.

Communication is defi ned simply as the clear and accurate sending and receiving of information, instructions, or commands, and providing useful feedback. Communication is a two-way process and should continue in a loop fashion.

Decision making is the ability to use logical and sound judgment to make decisions based on avail- able information. Decision-making processes are involved when a less experienced clinician seeks out the advice of a more experienced clinician or when a person defers important clinical decisions because of fatigue. Good decision making is based on real- ization of personal limitations.

Leadership is the ability to direct and coordinate the activities of other crew members and to encour- age the crew to work together as a team. *Analysis* refers to the ability to develop short-term, long- term, and contingency plans, as well as to coordi- nate, allocate, and monitor crew and operating room resources.

Th e last and most important principle is *situ- ational awareness ;* that is, the accuracy with which a person's perception of the current environment mir- rors reality. In the operating room, lack of situational awareness can cost precious minutes, as when read- ings from a monitor (eg, capnograph or arterial line) suddenly change and the operator focuses on the monitor rather than on the patient, who may have had an embolism. One must decide whether the monitor is correct and the patient is critically ill or the monitor is incorrect and the patient is fi ne. Th e problem-solving method utilized should consider both possibilities but quickly eliminate one. In this scenario, tunnel vision can result in catastrophic mistakes. Furthermore, if the sampling line has come loose and the capnograph indicates low end-tidal CO_2, this fi nding does not exclude the possibility that at the same time or even a bit later, the patient could have a pulmonary embolus resulting in decreased end-tidal CO_2.

If all members of the operating room team apply these seven principles, problems arising from human factors can almost entirely be eliminated. A culture of safety must also exist if the operating room is to be made a safer place. Th ese seven prin- ciples serve no purpose when applied in a suppres- sive surgical environment. Anyone with a concern must be able speak up without fear of repercussion.

Chapter 58 provides further discussion of these and other issues relating to patient safety.

FUTURE DESIGN OF OPERATING ROOMS

Safety Interlock Technology

Despite heightened awareness of safety factors and increased educational eff orts among operating room personnel, harm to patients still occurs at a rate that most industries and the public deem unacceptably high. Similarly, despite threats of payment withhold- ing, public scoring of medical personnel and hospital systems, provider rating web sites, and punitive legal consequences, the human factors resulting in medi- cal errors have not been completely eliminated. In future, safety-engineered designs may assist in the reduction of medical errors. One developing area is the use of interlock devices in the operating room. An interlock device is simply a device that cannot be operated until a defi ned sequence of events occurs. Anesthesia personnel use interlock technology with anesthesia vaporizers that prevent the use of more than one vaporizer at a time. Expansion of this tech- nology might prevent release of a drug from an auto- mated dispensing device until a barcode is scanned from a patient's hospital armband or, at a minimum, the patient's drug allergies have been entered into the machine's database. Other applications might include an electrosurgical device or laser that could not be used when the FiO_2 content was higher than 30%, thus eliminating the risk of fi re. Likewise, computers, monitors, and other devices could be designed to be inoperable until patient identifi cation was confi rmed.

Workfl ow Design

Coordinating the activities of surgical personnel, anesthesia providers, and operating room nurses is essential to the day-to-day running of a surgical suite. Clinical directors in facilities ranging from one- or two-room suites to multiroom centers must accommodate surgical procedures of varying dura- tions, requiring varying degrees of surgical skill and effi ciency, while allowing for sudden, unplanned, or emergency operations. Th e need to monitor work- fl ow and analyze data for optimizing scheduling and staffi ng prompted the development of soft ware sys- tems that anticipate and record the timing of surgical events; these systems are constantly being refi ned.

Surgical suites are also being designed to aug- ment workfl ow by incorporating separate induction areas to decrease nonsurgical time spent in operat- ing rooms. Several models exist for induction room design and staffi ng. Although uncommon in the United States, induction rooms have long been employed in the United Kingdom.

One induction room model uses rotating anes- thesia teams. One team is assigned to the fi rst patient of the day; a second team induces anesthesia for the next patient in an adjacent area while the operating room is being turned over. Th e second team contin- ues caring for that patient aft er transfer to the oper- ating room, leaving the fi rst team available to induce anesthesia in the third patient as the operating room is being turned over. Th e advantage of this model is continuity of care; the disadvantage is the need for two anesthesia teams for every operating room.

Another model uses separate induction and anesthesia teams. Th e induction team induces anes- thesia for all patients on a given day and then trans- fers care to the anesthesia team, which is assigned to an individual operating room. Th e advantage of this model is the reduction in anesthesia personnel to staff induction rooms; disadvantages include fail- ure to maintain continuity of care and staffi ng prob- lems that occur when several patients must undergo induction concurrently. Th is model can utilize either a separate induction room adjacent to each operat- ing room or one common induction room that ser- vices several operating rooms.

Th e fi nal model uses several staff ed operating rooms, one of which is kept open. Aft er the fi rst patient of the day is transferred to the initial room, subsequent patients always proceed to the open room, thus eliminating the wait for room turnover and readiness of personnel. All of these models assume that the increased overhead cost of main- taining additional anesthesia personnel can be justi- fi ed by the increased surgical productivity.

Radio Frequency Identifi cation (RFID)

Radio frequency identifi cation (RFID) technol- ogy utilizes a chip with a small transmitter whose

signal is read by a reader; each chip yields a unique signal. Th e technology has many potential applica- tions in the modern operating room. Using RFID in employee identifi cation (ID) badges could enable surgical control rooms to keep track of nursing, sur- gical faculty, and anesthesia personnel, obviating the need for paging systems and telephony to estab- lish the location of key personnel. Incorporating the technology in patient ID bands and hospital gurneys could allow a patient's fl ow to be tracked through an entire facility. Th e ability to project an identifying signal to hospital systems would off er an additional degree of safety for patients unable to communicate with hospital personnel. Finally, RFID could be incorporated into surgical instruments and sponges, allowing surgical counts to be performed by identifi cation of the objects as they are passed on and off the surgical fi eld. In the event that counts are mismatched, a wand could then be placed over the patient to screen for retained objects.

E DISCUSSION

Monitored Anesthesia Care with Oxygen Supplementation

You are asked to provide monitored anesthesia care for a patient undergoing simple removal of a lesion on the cheek. The patient is morbidly obese and has a history of sleep apnea. He states, "It bothers me when people are working on my face," and indicates that he does not want to remember anything about the surgery. The surgeon assures you the procedure will not last more than 5 minutes. The patient's wife mentions that they are from out of town and have made fl ight arrangements to return home soon after the procedure .

What features of this case indicate a high risk for surgical fi re?

Patients with a clinical history of obstructive sleep apnea usually have a sensitivity to sedating medications, especially opioid narcotics. Typically administration of even small doses of narcotics obstructs the upper airways, resulting in hypoventilation and hypercapnia. In the obese patient, this response combined with decreased functional reserve capacity results in rapid oxygen desaturation. Most anesthesia providers respond by increasing the amount of oxygen supplementation delivered via face mask or nasal cannula. Open delivery of oxygen in concentrations greater than 30% is one of the elements of the fi re triad. Another consideration is the anatomical location of the procedure. A location above the xiphoid process in this patient would place an ignition source (if used) in close proximity to the open delivery of an oxidizer .

What is the safest manner in which to proceed?

There are three strategies that can be implemented to improve safety in this scenario: avoid oxygen supplementation, secure the airway with an endotracheal tube or supraglottic device, or avoid use of an ignition source .

Are there any concerns relating to airway management or selection of the delivery device?

As previously noted, the patient is likely to manifest airway changes associated with obstructive sleep apnea and obesity. Selection of a delivery device should take into consideration the need to prevent the open delivery of oxygen .

How would the length of the procedure aff ect the management of anesthesia?

Practically speaking, if the patient requires a lengthy procedure, local anesthetics may wear off ; the cumulative dose of narcotics provided may exacerbate the patient's obstructive sleep apnea and increase recovery time. Additionally, more complex surgical excision may result in bleeding requiring the use of cautery .

Does the patient's expectation of discharge soon after the procedure aff ect your anesthesia plans?

The expectation of an accelerated recovery period may not be feasible if the patient requires general anesthesia or signifi cant amounts of opioid narcotics. The American Society of Anesthesiologists (ASA) has published a practice advisory providing direction for the safe postoperative assessment and discharge of patients with obstructive sleep apnea . See www.asahq.org.

What if the surgeon thinks your plans are "overkill"?

The first and most effective means for conflict resolution is to communicate your specific concerns to the surgeon. If this fails, the procedure must not be allowed to proceed as long as any team member has a legitimate safety concern. Many ASA safety-related guidelines and advisories are also endorsed by professional societies such as the American College of Surgeons (ACS) and other organizations. The anesthesiologist should also gain familiarity with a facility's methods of dispute resolution before an event occurs .

SUGGESTED READING

Dorsch JA, Dorsch SE: *Understanding Anesthesia Equipment* , 5th ed. Williams & Wilkins, 2008. A detailed discussion of compressed gases and medical gas delivery systems.

Macdonald MR, Wong A, Walker P, Crysdale WS: Electrocautery-induced ignition of tonsillar packing. J Otolaryngol 1994;23:426. An examination of factors that can decrease the risk of airway fire including lower oxygen concentration (using a cuffed tracheal tube), completely soaked tonsil packs, and avoidance of contact between electrocautery and bismuth subgallate.

National Fire Protection Association (NFPA): *Standard for Health Care Facilities* . NFPA, 2002. An updated version of NFPA 99 standards.

WEB SITES

http://www.ansi.org
The American National Standards Institute is the reference source for laser standards and many other protective engineering standards. http://www.apsf.org

The Anesthesia Patient Safety Foundation provides resources and a newsletter that discusses important safety issues in anesthesia. The web site also contains a link to view or request the video *Prevention and Management of Operating Room Fires* , which is an excellent resource to gain information concerning the risks and prevention of surgical fires. http://www.asahq.org

The American Society of Anesthesiologists (ASA) web site contains the ASA practice parameters and advisories. Many are oriented around patient safety issues and all can be printed for review. http://www.cganet.com

The Compressed Gas Association and its web site are dedicated to the development and promotion of safety standards and safe practices in the industrial gas industry. http://www.ecri.org

The ECRI (formerly the Emergency Care Research Institute) is an independent nonprofit health services research agency that focuses on health care technology, health care risk and quality management, and health care environmental management. http://www.fda.org

The U.S. Food and Drug Administration (FDA) has an extensive web site covering many broad categories. Two major divisions address patient safety: the Center for Devices and Radiological Health (CDRH), which regulates and evaluates medical devices, and the Center for Drug Evaluation and Research (CDER), which regulates and evaluates drugs. http://www.nfpa.org

The National Fire Protection Association (NPFA) has a web site with a catalog of publications on fire, electrical, and building safety issues. Some areas require a subscription to access. http://patientsafetyauthority.org The Patient Safety Authority maintains data collected from the mandatory reporting of incidents of harm or near harm in the Commonwealth of Pennsylvania. Some data such as surgical fires data can be extrapolated to determine the likely incidence for the entire United States. http://vam.anest.ufl .edu/

The Virtual Anesthesia Machine web site has extensive interactive modules to facilitate understanding of many processes and equipment. The site, which contains high-quality graphic illustrations and animation, requires free registration.

CHAPTER

33

Breathing Systems

Y CON C E P T S

Because insuffl ation avoids any direct patient contact, there is no rebreathing of exhaled gases if the fl ow is high enough. Ventilation cannot be controlled with this technique, however, and the inspired gas contains unpredictable amounts of entrained atmospheric air .

Long breathing tubes with high compliance increase the diff erence between the volume of gas delivered to a circuit by a reservoir bag or ventilator and the volume actually delivered to the patient .

The adjustable pressure-limiting (APL) valve should be fully open during spontaneous ventilation so that circuit pressure remains negligible throughout inspiration and expiration .

Because a fresh gas fl ow equal to minute ventilation is suffi cient to prevent rebreathing, the Mapleson A design is the most effi cient Mapleson circuit for spontaneous ventilation .

The Mapleson D circuit is effi cient during controlled ventilation, because fresh gas fl ow forces alveolar air away from the patient and toward the APL valve .

6 The drier the soda lime, the more likely it will absorb and degrade volatile anesthetics . Malfunction of either

7 unidirectional valve in a circle system may allow rebreathing of carbon dioxide, resulting in hypercapnia . With an absorber, the circle system prevents rebreathing

8 of carbon dioxide at fresh gas fl ows that are considered low (fresh gas fl ow ≤ 1 L) or even fresh gas fl ows equal to the uptake of anesthetic gases and oxygen by the patient and the circuit itself (closedsystem anesthesia) . Because of the unidirectional valves, apparatus dead space in a circle system is limited to the area distal to the point of inspiratory and expiratory gas mixing at the

9 Y-piece. Unlike Mapleson circuits, the circle system tube length does not directly aff ect dead space . The fraction of inspired oxygen (F_{IO_2}) delivered by a resuscitator breathing system to the patient is directly proportional to the oxygen concentration and fl ow rate of the gas mixture supplied to the resuscitator (usually 100% oxygen) and inversely proportional to the minute

10 ventilation delivered to the patient .

Breathing *systems* provide the fi nal conduit for the delivery of anesthetic gases to the patient. Breathing *circuits* link a patient to an anesthe- sia machine (Figure 3–1). Many diff erent circuit designs have been developed, each with varying degrees of effi ciency, convenience, and complexity. Th is chapter reviews the most important breath- ing systems: insuffl ation, draw-over, Mapleson circuits, the circle system, and resuscitation systems.

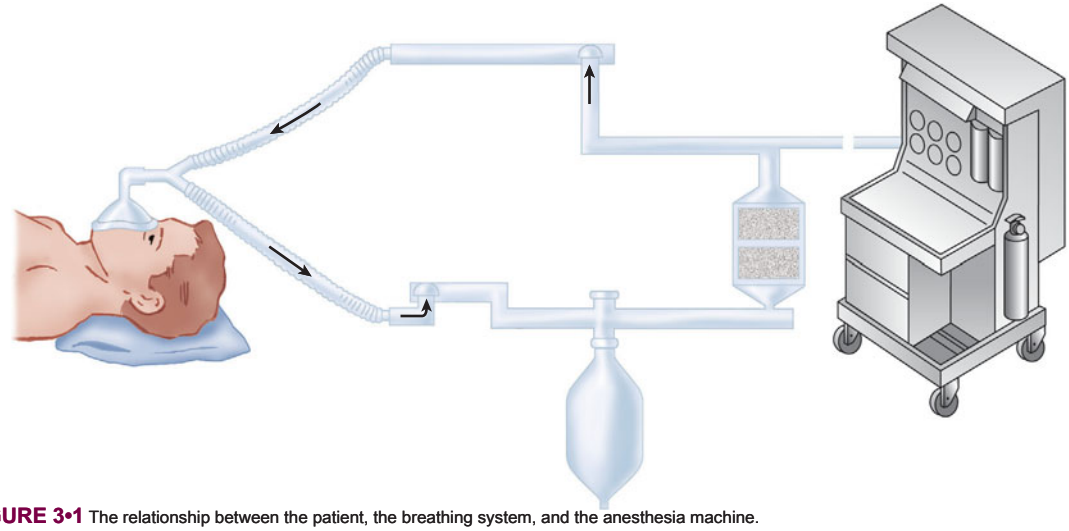


FIGURE 3•1 The relationship between the patient, the breathing system, and the anesthesia machine.

Most classifi cations of breathing systems artifi - cially consolidate functional characteristics (eg, the extent of rebreathing) with physical characteristics (eg, the presence of unidirectional valves). Because these seemingly contradictory classifi cations (eg, open, closed, semiopen, semiclosed) oft en tend to confuse rather than aid understanding, they are avoided in this discussion.

INSUFFLATION

Th e term insuffl ation usually denotes the blowing of anesthetic gases across a patient's face. Although insuffl ation is categorized as a breathing system, it is perhaps better considered a technique that avoids direct connection between a breathing circuit and a patient's airway. Because children oft en resist the placement of a face mask (or an intravenous line), insuffl ation is particularly valuable during induc- tions with inhalation anesthetics in children (Figure 3–2). It is useful in other situations as well. Carbon dioxide accumulation under head and neck draping is a hazard of ophthalmic surgery performed with local anesthesia. Insuffl ation of air across the patient's face at a high fl ow rate (>10 L/min) avoids this problem, while not increas- ing the risk of fi re from accumulation of oxygen (Figure 3–3). Because insuffl ation avoids any direct patient contact, there is no rebreathing of exhaled gases if the fl ow is high enough. Ventilation cannot be controlled with this technique, however, and the inspired gas contains unpredictable amounts of entrained atmospheric air.

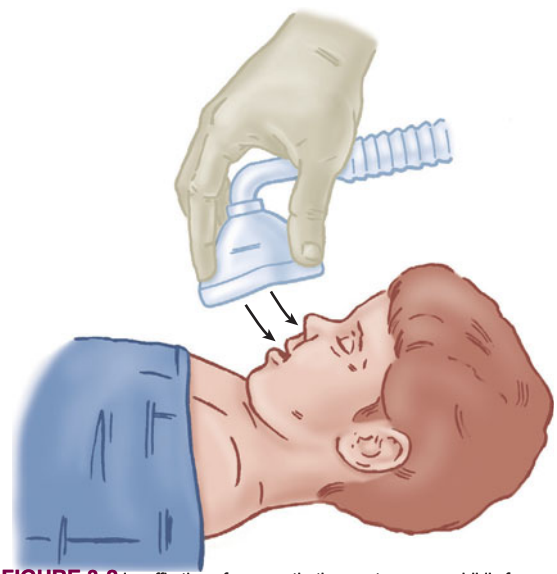


FIGURE 3•2 Insuffl ation of an anesthetic agent across a child's face during induction.

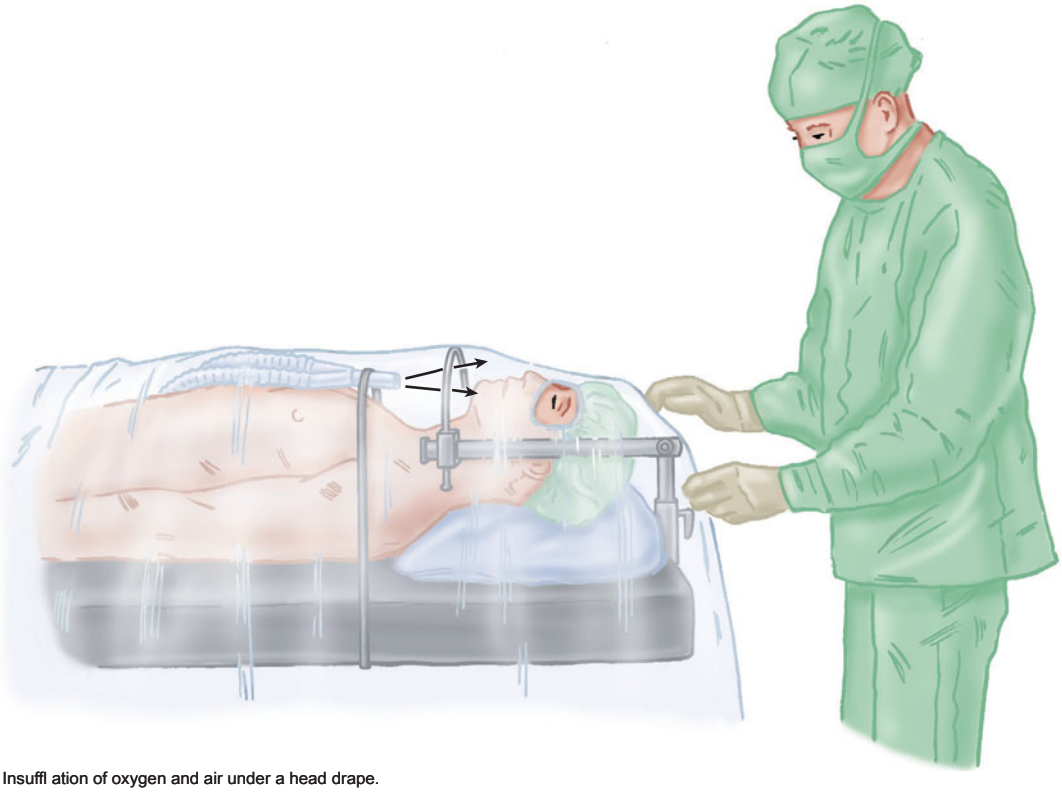


FIGURE 3•3 Insuffl ation of oxygen and air under a head drape.

Insuffl ation can also be used to maintain arterial oxygenation during brief periods of apnea (eg, dur- ing bronchoscopy). Instead of blowing gases across the face, oxygen is directed into the lungs through a device placed in the trachea.

OPEN•DROP ANESTHESIA

Although open-drop anesthesia is not used in mod- ern medicine, its historic signifi cance warrants a brief description here. A highly volatile anesthetic— historically, ether or chloroform—was dripped onto a gauze-covered mask (Schimmelbusch mask) applied to the patient's face. As the patient inhales, air passes through the gauze, vaporizing the liquid agent, and carrying high concentrations of anes- thetic to the patient. Th e vaporization lowers mask temperature, resulting in moisture condensation and a drop in anesthetic vapor pressure (vapor pres- sure is proportional to temperature).

A modern derivative of open-drop anesthe- sia utilizes draw-over vaporizers that depend on the patient's inspiratory eff orts to draw ambient air through a vaporization chamber. Th is tech- nique may be used in locations or situations in which compressed medical gases are unavailable (eg, battlefi elds).

DRAW•OVER ANESTHESIA

Draw-over devices have nonrebreathing circuits that use ambient air as the carrier gas, although supplemental oxygen can be used, if available. Th e devices can be fi tted with connections and equip- ment that allow intermittent positive-pressure ven- tilation (IPPV) and passive scavenging, as well as

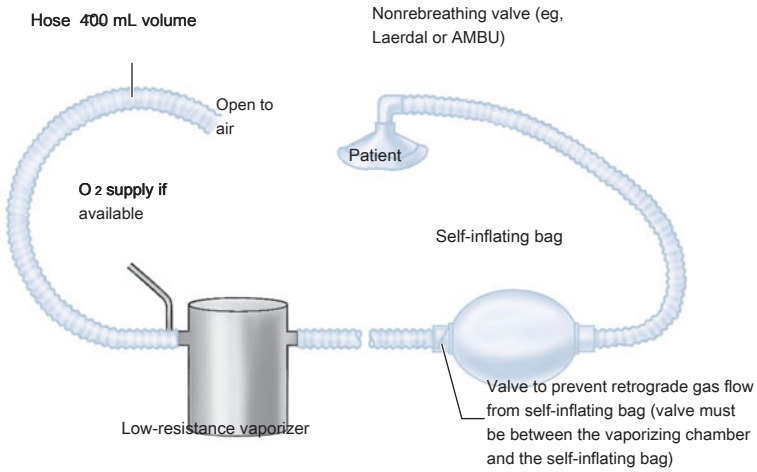


FIGURE 3•4 Schematic diagram of a draw-over anesthesia device/circuit.

continuous positive airway pressure (CPAP) and positive end-expiratory pressure (PEEP).

In its most basic application (Figure 3–4), air is drawn through a low-resistance vaporizer as the patient inspires. Patients spontaneously breathing room air and a potent halogenated agent often manifest an oxygen saturation (SpO_2) < 90%, a situation treated with IPPV, supplemental oxygen, or both. The fraction of inspired oxygen (FiO_2) can be supplemented using an open-ended reservoir tube of about 400 mL, attached to a t-piece at the upstream side of the vaporizer. Across the clinical range of tidal volume and respiratory rate, an oxygen flow rate of 1 L/min gives an FiO_2 of 30% to 40%, or with 4 L/min, an FiO_2 of 60% to 80%. There are several commercial draw-over systems available that share common properties (Table 3–1).

The greatest advantage of draw-over systems is their simplicity and portability, making them useful in locations where compressed gases or ventilators are not available. The presence of the nonrebreathing valve, PEEP valve, and circuit filter close to the patient's head makes the technique awkward for head and neck surgery and pediatric cases. If the head is draped, the nonrebreathing valve is often covered as well.

The original design of a draw-over system has recently been modified to include a self-inflating bag, a ventilator, and/or a heat and moisture exchanger. The Ohmeda Universal Portable Anesthesia Complete (U-PAC) is one example of a draw-over anesthesia system.

TABLE 3•1 Properties of draw-over devices.

Portable
Low resistance to gas flow
Usable with any agent[1]
Controllable vapor output

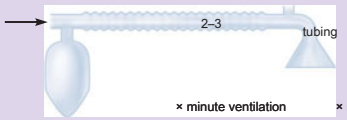
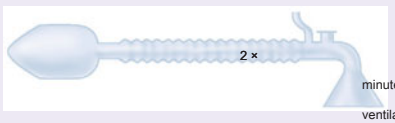
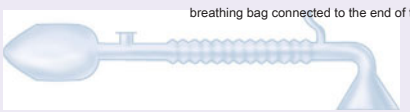
[1] Halothane cannot be used with the Epstein Mackintosh Oxford device.

MAPLESON CIRCUITS

The insufflation and draw-over systems have several disadvantages: poor control of inspired gas concentration (and, therefore, poor control of depth of anesthesia), mechanical drawbacks during head and neck surgery, and pollution of the operating room with large volumes of waste gas. The **Mapleson systems** solve some of these problems by incorporating additional components (breathing tubes, fresh gas inlets, adjustable pressure-limiting [APL] valves, and reservoir bags) into the breathing circuit. The relative location of these components determines circuit performance and is the basis of the Mapleson classification (Table 3–2).

FGI valve APL valve Breathing tube ventilaton.

FGI APL Breathing bag Mask valve

	FGI	FGI	FGI	APL valve	APL valve	cotrolled
	2–3 × minute ventilation	2–3 × minute ventilation	2–3 × minute ventilation	2 × minute ventilation	2 × minute ventilation	Equal to minute ventilation (= 80 mL/kg/min)
	2 × minute ventilation	3 × minute ventilation (I:E-1:2)	1–2 × minute ventilation	2–2½ × minute ventilation	2–2½ × minute ventilation	Very high and diffi cult to predict
	A Mapleson E with a breathing bag connected to the end of the breathing tube to allow controlled ventilation and scavenging.	Exhalation	Bain			Poor
						
		coaxial modifi cation: fresh gas tube inside breathing tube (see Figure 3–7).				
						

Spontaneous	**Required**
Controlled	**Comments**

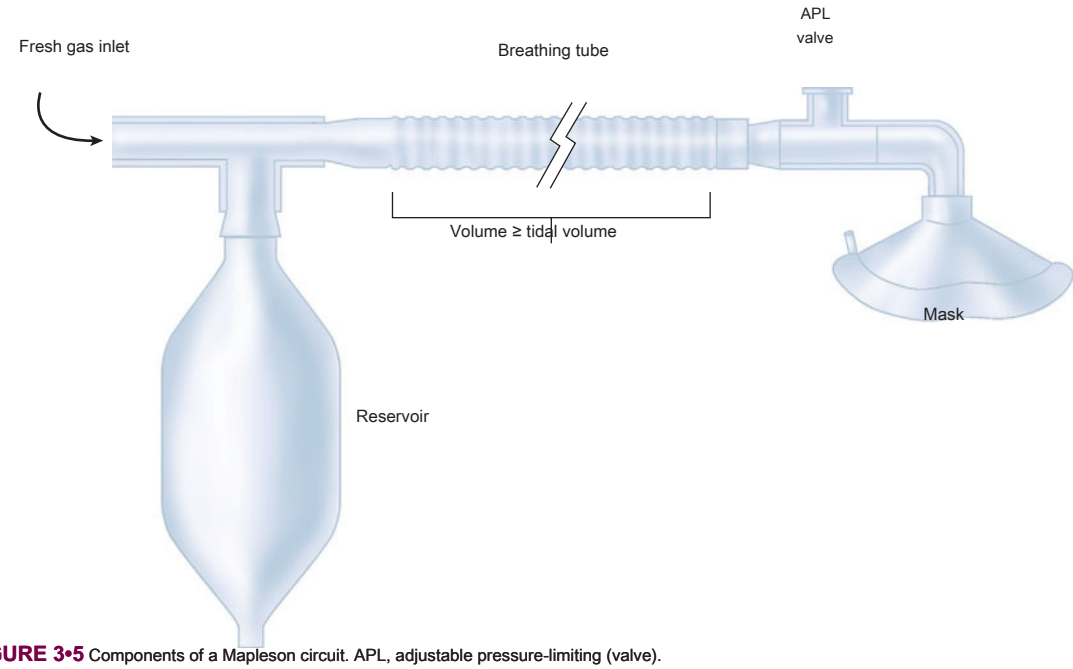


FIGURE 3•5 Components of a Mapleson circuit. APL, adjustable pressure-limiting (valve).

Components of Mapleson Circuits

A. Breathing Tubes

Corrugated tubes—made of rubber (reusable) or plastic (disposable)—connect the components of the Mapleson circuit to the patient (Figure 3–5). Th e large diameter of the tubes (22 mm) creates a low-resistance pathway and a potential reservoir for anesthetic gases. To minimize fresh gas fl ow require- ments, the volume of gas within the breathing tubes in most Mapleson circuits should be at least as great as the patient's tidal volume.

Th e compliance of the breathing tubes largely determines the compliance of the circuit. (Compli- ance is defi ned as the change of volume produced by a change in pressure.) Long breathing tubes with high compliance increase the diff erence between the volume of gas delivered to a circuit by a reservoir bag or ventilator and the volume actually delivered to the patient. For example, if a breathing circuit with a compliance of 8 mL gas/cm H_2O is pressurized during delivery of a tidal volume to 20 cm H_2O, 160 mL of the tidal volume will be lost to the circuit. Th e 160 mL represent a combination of gas compression and breathing-tube expansion. Th is is an important consideration in any circuit deliver- ing positive-pressure ventilation through breathing tubes (eg, circle systems).

B. Fresh Gas Inlet

Gases (anesthetics mixed with oxygen or air) from the anesthesia machine continuously enter the circuit through the fresh gas inlet. As discussed below, the relative position of the fresh gas inlet is a key diff erentiating factor in Mapleson circuit performance.

C. Adjustable Pressure-Limiting Valve (Pressure-Relief Valve, Pop-Off Valve)

As anesthetic gases enter the breathing circuit, pres- sure will rise if the gas infl ow is greater than the combined uptake of the patient and the circuit. Gases may exit the circuit through an APL valve, controlling this pressure buildup. Exiting gases enter the operating room atmosphere or, preferably, a waste-gas scavenging system. All APL valves allow a variable pressure threshold for venting. Th e APL valve should be fully open during

spontaneous ventilation so that circuit pressure remains negligible throughout inspiration and expi- ration. Assisted and controlled ventilation require positive pressure during inspiration to expand the lungs. Partial closure of the APL valve limits gas exit, permitting positive circuit pressures during reser- voir bag compressions.

D. Reservoir Bag (Breathing Bag)

Reservoir bags function as a reservoir of anesthetic gas and a method of generating positive-pressure ventilation. Th ey are designed to increase in compli- ance as their volume increases. Th ree distinct phases of reservoir bag fi lling are recognizable (Figure 3–6).

Aft er the nominal 3-L capacity of an adult reservoir bag is achieved (phase I), pressure rises rapidly to a peak (phase II). Further increases in volume result in a plateau or even a slight decrease in pressure (phase III). Th is ceiling eff ect provides some mini- mal protection of the patient's lungs against high airway pressures, if the APL valve is unintentionally left in the closed position while fresh gas continues to fl ow into the circuit.

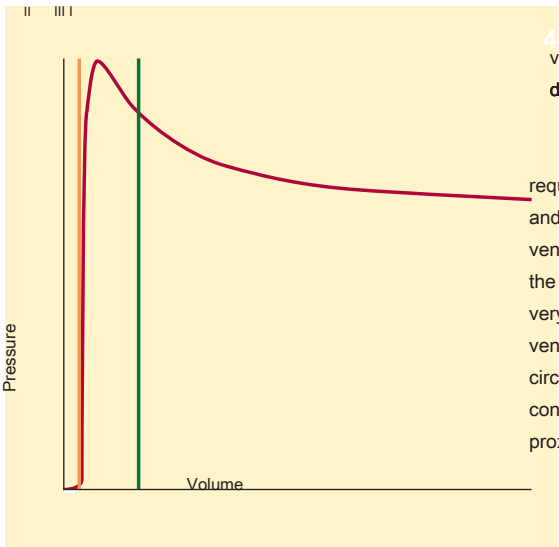


FIGURE 3•6 The increasing compliance and elasticity of breathing bags as demonstrated by three phases of fi lling (see text). (Reproduced, with permission, from Johnstone RE, Smith TC: Rebreathing bags as pressure limiting devices. Anesthesiology 1973;38:192.)

Performance Characteristics of Mapleson Circuits

Mapleson circuits are lightweight, inexpensive, and simple. Breathing-circuit effi ciency is measured by the fresh gas fl ow required to reduce CO_2 rebreathing to a negligible value. Because there are no unidirec- tional valves or CO_2 absorption in Mapleson circuits, rebreathing is prevented by adequate fresh gas fl ow into the circuit and venting exhaled gas through the APL valve before inspiration. Th ere is usually some rebreathing in any Mapleson circuit. Th e total fresh gas fl ow into the circuit controls the amount. To attenuate rebreathing, high fresh gas fl ows are required. Th e APL valve in Mapleson A, B, and C cir- cuits is located near the face mask, and the reservoir bag is located at the opposite end of the circuit.

Reexamine the drawing of a Mapleson A circuit in Figure 3–5 . During spontaneous ventilation, alveo- lar gas containing CO_2 will be exhaled into the breath- ing tube or directly vented through an open APL valve. Before inhalation occurs, if the fresh gas fl ow exceeds alveolar minute ventilation, the infl ow of fresh gas will force the alveolar gas remaining in the breath- ing tube to exit from the APL valve. If the breathing- tube volume is equal to or greater than the patient's tidal volume, the next inspiration will contain only fresh gas. Because a fresh gas fl ow equal to min- ute ventilation is suffi cient to prevent rebreath- ing, the Mapleson A design is the most effi cient Mapleson circuit for *spontaneous* ventilation.

Positive pressure during *controlled* ventila- tion, however, requires a partially closed APL valve. Although some alveolar and fresh gas exits through the valve during inspiration, no gas is vented during expiration, since the exhaled gas stagnates during the expiratory phase of positive pressure ventilation. As a result, very high fresh gas fl ows (greater than three times minute ventilation) are required to prevent rebreathing with a Mapleson A circuit during con- trolled ventilation. Fresh gas fl ows are conveniently available because the fresh gas inlet is in close prox- imity to the APL valve in a Mapleson B circuit.

Interchanging the position of the APL valve and the fresh gas inlet transforms a Mapleson A into a

Mapleson D circuit (Table 3–2). Th e Mapleson D circuit is effi cient during controlled ventila- tion, since fresh gas fl ow forces alveolar air *away*

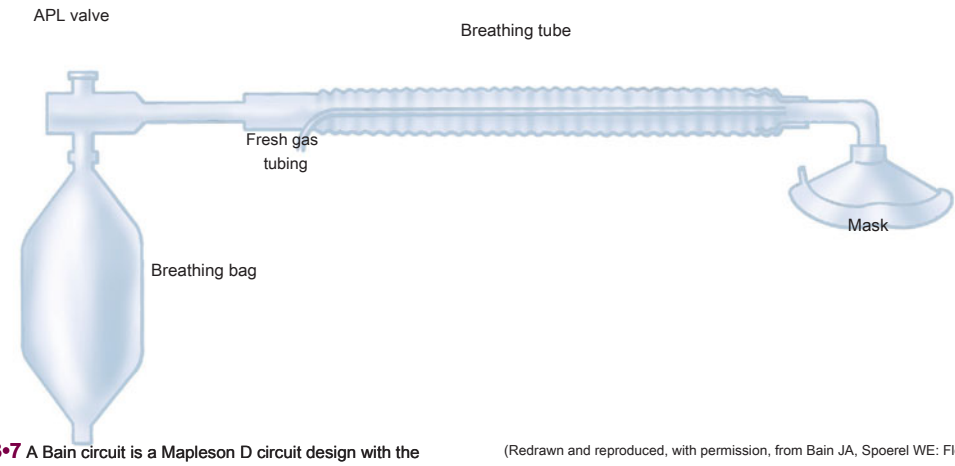


FIGURE 3•7 A Bain circuit is a Mapleson D circuit design with the fresh gas tubing inside the corrugated breathing tube. APL, adjustable pressure-limiting (valve).

(Redrawn and reproduced, with permission, from Bain JA, Spoerel WE: Flow requirements for a modifi ed Mapleson D system during controlled ventilation. Can Anaesth Soc J 1973;20:629.)

from the patient and *toward* the APL valve. Th us, simply moving components completely alters the fresh gas requirements of the Mapleson circuits.

Th e **Bain circuit** is a coaxial version of the Mapleson D system that incorporates the fresh gas inlet tubing inside the breathing tube (Figure 3–7).

Th is modifi cation decreases the circuit's bulk and retains heat and humidity better than a conventional Mapleson D circuit as a result of partial warming of the inspiratory gas by countercurrent exchange with the warmer expired gases. A disadvantage of this coaxial circuit is the possibility of kinking or discon- nection of the fresh gas inlet tubing. Periodic inspec- tion of the inner tubing is mandatory to prevent this complication; if unrecognized, either of these mishaps could result in signifi cant rebreathing of exhaled gas.

THE CIRCLE SYSTEM

Although Mapleson circuits overcome some of the disadvantages of the insuffl ation and draw-over sys- tems, the high fresh gas fl ows required to prevent rebreathing of CO_2 result in waste of anesthetic agent, pollution of the operating room environment, and loss of patient heat and humidity (Table 3–3). In an attempt to avoid these problems, the **circle system** adds more components to the breathing system.

Th e components of a circle system include: (1) a CO_2 absorber containing CO_2 absorbent; (2) a fresh gas inlet; (3) an inspiratory unidirectional valve and inspiratory breathing tube; (4) a Y-connector; (5) an expiratory unidirectional valve and expiratory breathing tube; (6) an APL valve; and (7) a reservoir (Figure 3–8).

Components of the Circle System

A. Carbon Dioxide Absorber and the Absorbent

Rebreathing alveolar gas conserves heat and humid- ity. However, the CO_2 in exhaled gas must be elimi- nated to prevent hypercapnia. CO_2 chemically

TABLE 3•3 Characteristics of breathing circuits.

	Insuffl ation and Open Drop	Mapleson	
	Circle		
Complexity	Very simple	Simple	Complex
Control of anesthetic depth	Poor	Variable	Good
Ability to scavenge	Very poor	Variable	Good
Conservation of heat and humidity	No	No	Yes [1]
Rebreathing of exhaled gases	No	No [1]	Yes [1]

[1] These properties depend on the rate of fresh gas fl ow.

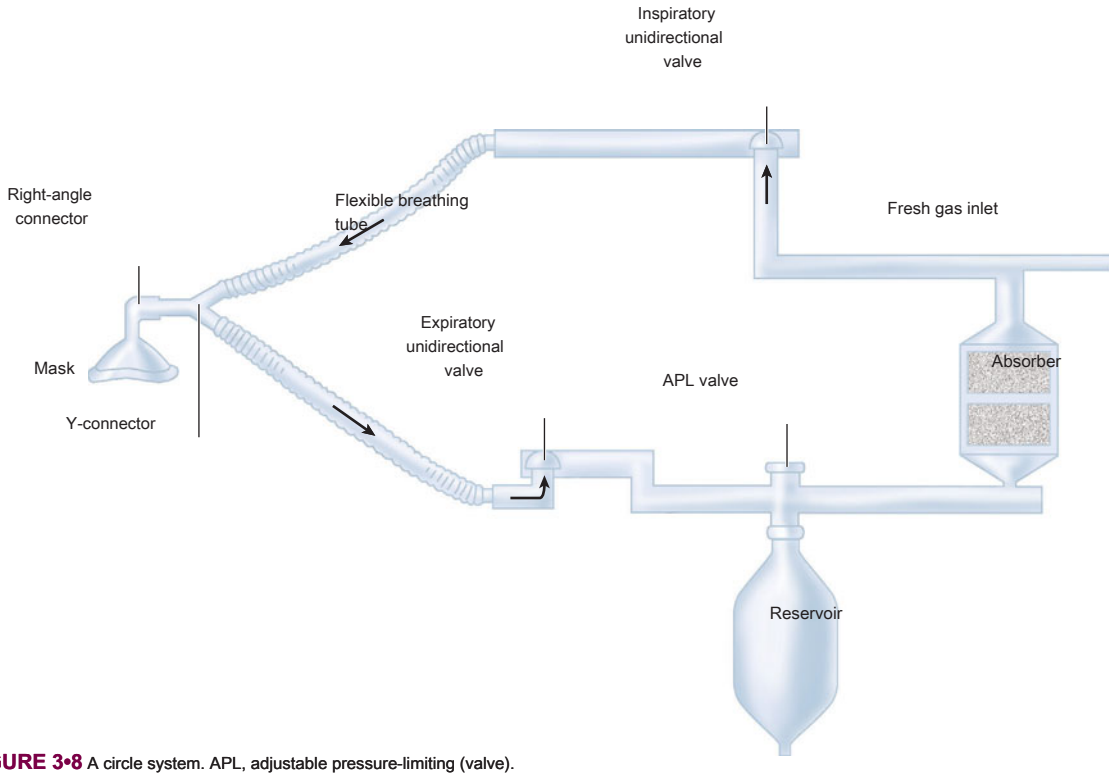


FIGURE 3•8 A circle system. APL, adjustable pressure-limiting (valve).

combines with water to form carbonic acid. CO_2 absorbents (eg, soda lime or calcium hydroxide lime) contain hydroxide salts that are capable of neutralizing carbonic acid (Table 3–4). Reaction end products include heat (the heat of neutralization), water, and calcium carbonate. **Soda lime** is the more common absorbent and is capable of absorb- ing up to 23 L of CO_2 per 100 g of absorbent. It con- sists primarily of calcium hydroxide (80%), along with sodium hydroxide, water, and a small amount of potassium hydroxide. Its reactions are as follows:

$$CO_2 + H_2O \rightarrow H_2CO_3$$

$$H_2CO_3 + 2NaOH \rightarrow Na_2CO_3 + 2H_2O + \text{Heat}$$

(a fast reaction)

$$Na_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2NaOH$$

(a slow reaction)

Note that the water and sodium hydroxide ini- tially required are regenerated. Another absorbent, barium hydroxide lime, is no longer used due to the

TABLE 3•4 Comparison of soda lime and barium hydroxide lime.

	Soda Lime	Barium Hydroxide Lime
Mesh size[1]	4–8	4–8
Method of hardness	Silica added	Water of crystallization
Content	Calcium hydroxide Sodium hydroxide Potassium hydroxide	Barium hydroxide Calcium hydroxide
Usual indicator dye	Ethyl violet	Ethyl violet
Absorptive capacity (liters of CO_2/ 100 g granules)	14–23	9–18

[1] The number of openings per linear inch in a wire screen used to grade particle size.

TABLE 3•5 Indicator dye changes signaling absorbent exhaustion.

Indicator	Color when Fresh	Color when Exhausted
Ethyl violet	White	Purple
Phenolphthalein	White	Pink
Clayton yellow	Red	Yellow
Ethyl orange	Orange	Yellow
Mimosa 2	Red	White

possible increased hazard of fi re in the breathing system.

A pH indicator dye (eg, ethyl violet) changes color from white to purple as a consequence of increasing hydrogen ion concentration and absorbent exhaus- tion (Table 3–5). Absorbent should be replaced when 50% to 70% has changed color. Although exhausted granules may revert to their original color if rested, no signifi cant recovery of absorptive capac- ity occurs. Granule size is a compromise between the higher absorptive surface area of small granules and the lower resistance to gas fl ow of larger granules. Th e granules commonly used as CO_2 absorbent are between 4 and 8 mesh; the number of mesh corre- sponds to the number of holes per square inch of a screen. Th e hydroxide salts are irritating to the skin and mucous membranes. Increasing the hardness of soda lime by adding silica minimizes the risk of inha- lation of sodium hydroxide dust and also decreases resistance of gas fl ow. Additional water is added to absorbent during packaging to provide optimal con- ditions for carbonic acid formation. Commercial soda lime has a water content of 14% to 19%.

Absorbent granules can absorb and later release medically important amounts of volatile anesthetic. Th is property can be responsible for modest delays of induction or emergence. Th e drier the soda lime, the more likely it will absorb and degrade volatile anesthetics. Volatile anesthetics can be bro- ken down to carbon monoxide by dry absorbent (eg, sodium or potassium hydroxide) to such a degree that it is capable of causing clinically signifi cant car- bon monoxide poisoning. Th e formation of carbon monoxide is highest with desfl urane; with sevofl u- rane, it occurs at a higher temperature.

Amsorb is a CO_2 absorbent consisting of cal- cium hydroxide and calcium chloride (with calcium sulfate and polyvinylpyrrolidone added to increase hardness). It possesses greater inertness than soda lime, resulting in less degradation of volatile anes- thetics (eg, sevofl urane into compound A or desfl u- rane into carbon monoxide).

Compound A is one of the by-products of deg- radation of sevofl urane by absorbent. Higher con- centrations of sevofl urane, prolonged exposure, and low-fl ow anesthetic technique seem to increase the formation of Compound A. Compound A has been shown to produce nephrotoxicity in animals,

Th e granules of absorbent are contained within one or two canisters that fi t snugly between a head and base plate. Together, this unit is called an absorber (Figure 3–9). Although bulky, double

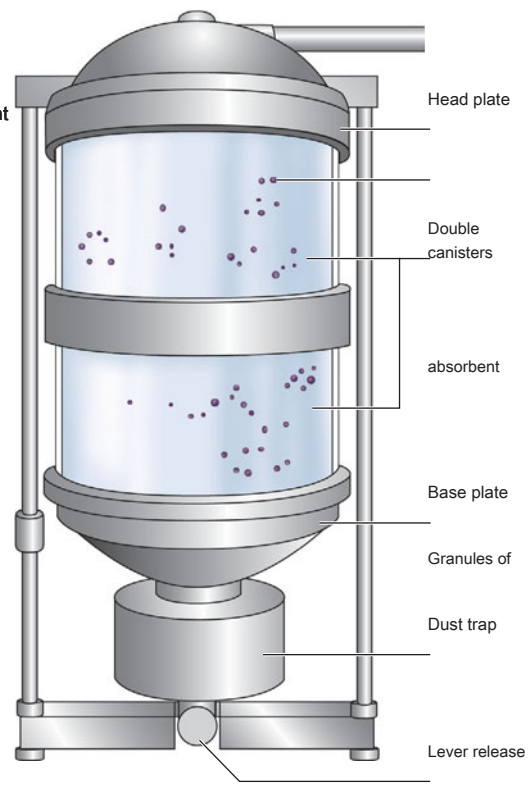


FIGURE 3•9 A carbon dioxide absorber.

canisters permit more complete CO_2 absorption, less frequent absorbent changes, and lower gas fl ow resistance. To ensure complete absorption, a patient's tidal volume should not exceed the air space between absorbent granules, which is roughly equal to 50% of the absorber's capacity. Indicator dye color is monitored through the absorber's trans- parent walls. Absorbent exhaustion typically occurs fi rst where exhaled gas enters the absorber and along the canister's smooth inner walls. Channeling through areas of loosely packed granules is mini- mized by a baffl e system, which directs gas fl ow through the center, thereby allowing greater utili- zation of the absorbent. A trap at the base of the absorber collects dust and moisture. Newer absorb- ers are used until CO_2 is found in the inhaled gas on the anesthetic-gas monitor, at which time the canister(s) are replaced.

B. Unidirectional Valves

Unidirectional valves, which function as check valves, contain a ceramic or mica disk resting hori- zontally on an annular valve seat (Figure 3–10).

Forward fl ow displaces the disk upward, permitting the gas to proceed through the circuit. Reverse fl ow pushes the disk against its seat, preventing refl ux. Valve incompetence is usually due to a warped disk or seat irregularities. Th e expiratory valve is exposed to the humidity of alveolar gas. Condensation and resultant moisture formation may prevent upward displacement of the disks, resulting in incomplete escape of expired gases and rebreathing.

Inhalation opens the inspiratory valve, allowing the patient to breathe a mixture of fresh and exhaled gas that has passed through the CO_2 absorber. Simultaneously, the expiratory valve closes to pre- vent rebreathing of exhaled gas that still contains CO_2. Th e subsequent fl ow of gas away from the patient during exhalation opens the expiratory valve. Th is gas is vented through the APL valve or rebreathed by the patient aft er passing through the absorber. Closure of the inspiratory valve during exhalation prevents expiratory gas from mixing with fresh gas in the inspiratory limb. Malfunction of either unidirectional valve may allow rebreathing of CO_2, resulting in hypercapnia.

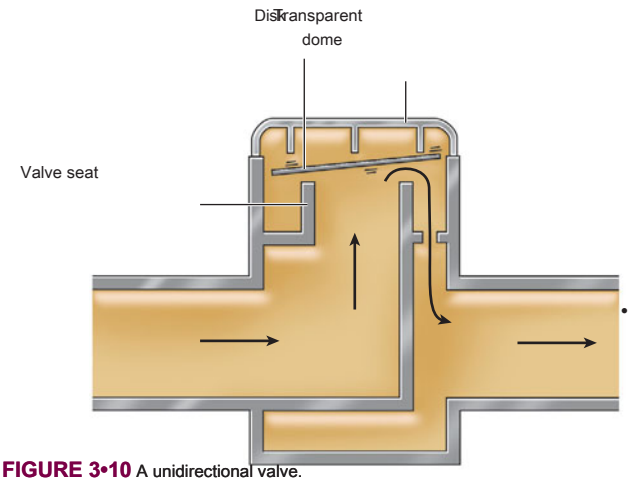


FIGURE 3•10 A unidirectional valve.

Optimization of Circle System Design

Although the major components of the circle system (unidirectional valves, fresh gas inlet, APL valve, CO_2 absorber, and a reservoir bag) can be placed in several confi gurations, the following arrangement is preferred (Figure 3–8):

- Unidirectional valves are relatively close to the patient to prevent backfl ow into the inspiratory limb if a circuit leak develops. However, unidirectional valves are not placed in the Y-piece, as that makes it diffi cult to confi rm proper orientation and intraoperative function.
- Th e fresh gas inlet is placed between the absorber and the inspiratory valve. Positioning it downstream from the inspiratory valve would allow fresh gas to bypass the patient during exhalation and be wasted. Fresh gas introduced between the expiratory valve and the absorber would be diluted by recirculating gas. Furthermore, inhalation anesthetics may be absorbed or released by soda lime granules, thus slowing induction and emergence.
- Th e APL valve is usually placed between the absorber and the expiratory valve and close to the reservoir bag. Positioning of the APL valve in this location (ie, before the absorber) helps to conserve absorption capacity and minimizes the venting of fresh gas.

- Resistance to exhalation is decreased by locating the reservoir bag in the expiratory limb. Bag compression during controlled ventilation will vent expired gas through the APL valve, conserving absorbent.

Performance Characteristics of the Circle System

A. Fresh Gas Requirement

With an absorber, the circle system prevents rebreathing of CO_2 at reduced fresh gas flows (≤1 L) or even fresh gas flows equal to the uptake of anesthetic gases and oxygen by the patient and the circuit itself (closed-system anesthesia). At fresh gas flows greater than 5 L/min, rebreathing is so minimal that a CO_2 absorber is usually unnecessary.

With low fresh gas flows, concentrations of oxygen and inhalation anesthetics can vary markedly between fresh gas (ie, gas in the fresh gas inlet) and inspired gas (ie, gas in the inspiratory limb of the breathing tubes). The latter is a mixture of fresh gas and exhaled gas that has passed through the absorber. The greater the fresh gas flow rate, the less time it will take for a change in fresh gas anesthetic concentration to be reflected in a change in inspired gas anesthetic concentration. Higher flows speed induction and recovery, compensate for leaks in the circuit, and decrease the risks of unanticipated gas mixtures.

B. Dead Space

That part of a tidal volume that does not undergo alveolar ventilation is referred to as dead space. Thus, any increase in dead space must be accompanied by a corresponding increase in tidal volume, if alveolar ventilation is to remain unchanged.

Because of the unidirectional valves, apparatus dead space in a circle system is limited to the area distal to the point of inspiratory and expiratory gas mixing at the Y-piece. Unlike Mapleson circuits, the circle system tube length does not affect dead space. Like Mapleson circuits, length does affect circuit compliance and thus the amount of tidal volume lost to the circuit during positive-pressure ventilation. Pediatric circle systems may have both a septum dividing the inspiratory and expiratory gas in the Y-piece and low-compliance breathing tubes to further reduce dead space, and are lighter in weight.

C. Resistance

The unidirectional valves and absorber increase circle system resistance, especially at high respiratory rates and large tidal volumes. Nonetheless, even premature neonates can be successfully ventilated using a circle system.

D. Humidity and Heat Conservation

Medical gas delivery systems supply dehumidified gases to the anesthesia circuit at room temperature. Exhaled gas, on the other hand, is saturated with water at body temperature. Therefore, the heat and humidity of inspired gas depend on the relative proportion of rebreathed gas to fresh gas. High flows are accompanied by low relative humidity, whereas low flows allow greater water saturation. Absorbent granules provide a significant source of heat and moisture in the circle system.

E. Bacterial Contamination

The minimal risk of microorganism retention in circle system components could theoretically lead to respiratory infections in subsequent patients. For this reason, bacterial filters are sometimes incorporated into the inspiratory or expiratory breathing tubes or at the Y-piece.

Disadvantages of the Circle System

Although most of the problems of Mapleson circuits are solved by the circle system, the improvements have led to other disadvantages: greater size and less portability; increased complexity, resulting in a higher risk of disconnection or malfunction; complications related to use of absorbent; and the difficulty of predicting inspired gas concentrations during low fresh gas flows.

RESUSCITATION BREATHING SYSTEMS

Resuscitation bags (AMBU bags or bag-mask units) are commonly used for emergency ventilation because of their simplicity, portability, and ability to deliver almost 100% oxygen (Figure 3–11). A

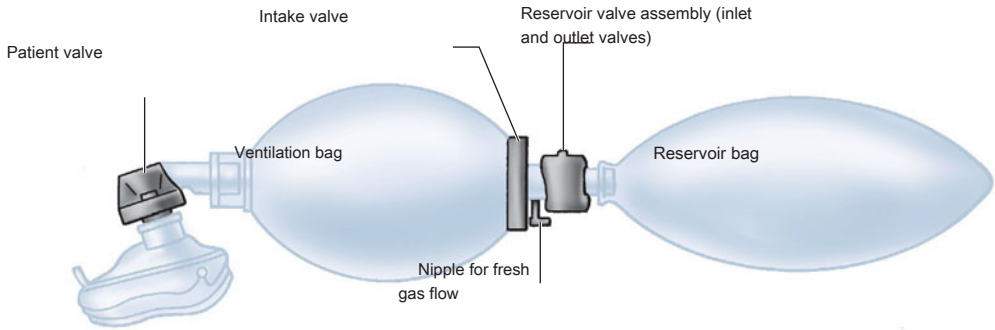


FIGURE 3•11 The Laerdal resuscitator. (Reproduced, with permission, from Laerdal Medical Corp.)

resuscitator is unlike a Mapleson circuit or a circle system **because it contains a nonrebreathing valve .** (Remember that a Mapleson system is considered valveless even though it contains an APL valve, whereas a circle system contains unidirectional valves that direct fl ow through an absorber but allow rebreathing of exhaled gases.)

High concentrations of oxygen can be delivered to a mask or tracheal tube during spontaneous or controlled ventilation if a source of high fresh gas fl ow is connected to the inlet nipple. Th e patient valve opens during controlled or spontaneous inspiration to allow gas fl ow from the ventilation bag to the patient. Rebreathing is prevented by venting exhaled gas to the atmosphere through exhalation ports in this valve. Th e compressible, self-refi lling ventilation bag also contains an intake valve. Th is valve closes during bag compression, permitting positive-pressure ventilation. Th e bag is refi lled by fl ow through the fresh gas inlet and across the intake valve. Connecting a reservoir to the intake valve helps prevent the entrainment of room air. Th e reservoir valve assembly is really two unidirectional valves: the inlet valve and the outlet valve. Th e inlet valve allows ambient air to enter the ventilation bag if fresh gas fl ow is inadequate to maintain reservoir fi lling. Positive pressure in the reservoir bag opens the outlet valve, which vents oxygen if fresh gas fl ow is excessive.

Th ere are several disadvantages to resuscitator breathing systems. First, they require high fresh gas fl ows to achieve a high F_{IO_2}. F_{IO_2} is directly pro- portional to the oxygen concentration and fl ow rate of the gas mixture supplied to the resuscitator (usually 100% oxygen) and inversely proportional to the minute ventilation delivered to the patient. For example, a Laerdal resuscitator equipped with a res- ervoir requires a fl ow of 10 L/min to achieve an inspired oxygen concentration approaching 100% if a patient with a tidal volume of 750 mL is ventilated at a rate of 12 breaths/min. Th e maximum achievable tidal volumes are less than those that can be achieved with a system that uses a 3-L breathing bag. In fact, most adult resuscitators have a maximum tidal vol- ume of 1000 mL, which is suffi cient for the lower tidal volumes generally employed in patient management. Finally, although a normally functioning patient valve has low resistance to inspiration and expiration, exhaled moisture can cause valve sticking.

DISCUSSION

Unexplained Light Anesthesia

An extremely obese but otherwise healthy 5-year-old girl presents for inguinal hernia repair. After uneventful induction of general anesthesia and tracheal intubation, the patient is placed on a ventilator set to deliver a tidal volume of 7 mL/kg at a rate of 16 breaths/min. Despite delivery of high concentrations of sevofl urane in 50% nitrous oxide, tachycardia (145 beats/min) and mild hypertension (144/94 mm Hg) are noted. To increase anesthetic depth, fentanyl (3 mcg/kg) is administered. Heart rate and blood pressure continue to rise and are accompanied by frequent premature ventricular contractions .

What should be considered in the diff erential diagnosis of this patient's cardiovascular changes?

The combination of tachycardia and hypertension during general anesthesia should always alert the anesthesiologist to the possibility of hypercapnia or hypoxia, both of which produce signs of increased sympathetic activity. These life- threatening conditions should be quickly and immediately ruled out by end-tidal CO_2 monitoring, pulse oximetry, or arterial blood gas analysis .

A common cause of intraoperative tachycardia and hypertension is an inadequate level of anesthesia. Normally, this is confi rmed by movement. If the patient is paralyzed, however, there are few reliable indicators of light anesthesia. The lack of a response to a dose of an opioid should alert the anesthesiologist to the possibility of other, perhaps more serious, causes .

Malignant hyperthermia is rare but must be considered in cases of unexplained tachycardia, especially if accompanied by premature contractions. Certain drugs used in anesthesia (eg, pancuronium, ketamine, ephedrine) stimulate the sympathetic nervous system and can produce or exacerbate tachycardia and hypertension. Diabetic patients who become hypoglycemic from administration of insulin or long-acting oral hypoglycemic agents can have similar cardiovascular changes. Other endocrine abnormalities (eg, pheochromocytoma, thyroid storm, carcinoid) should also be considered .

Could any of these problems be related to an equipment malfunction?

Gas analysis can confi rm the delivery of anesthetic gases to the patient .

A misconnection of the ventilator could result in hypoxia or hypercapnia. In addition, a malfunctioning unidirectional valve will increase circuit dead space and allow rebreathing of expired CO_2. Soda lime exhaustion could also lead to rebreathing in the presence of a low fresh gas fl ow. Rebreathing of CO_2 can be detected during the inspiratory phase on a capnograph. If rebreathing appears to be due to an equipment malfunction, the patient should be disconnected from the anesthesia machine and ventilated with a resuscitation bag until repairs are possible .

What are some other consequences of hypercapnia?

Hypercapnia has a multitude of eff ects, most of them masked by general anesthesia. Cerebral blood fl ow increases proportionately with arterial CO_2. This eff ect is dangerous in patients with increased intracranial pressure (eg, from brain tumor). Extremely high levels of CO_2 (> 80 mm Hg) can cause unconsciousness related to a fall in cerebrospinal fl uid pH. CO_2 depresses the myocardium, but this direct eff ect is usually overshadowed by activation of the sympathetic nervous system. During general anesthesia, hypercapnia usually results in an increased cardiac output, an elevation in arterial blood pressure, and a propensity toward arrhythmias .

Elevated serum CO_2 concentrations can overwhelm the blood's buff ering capacity, leading to respiratory acidosis. This causes other cations such as Ca^{2+} and K^+ to shift extracellularly. Acidosis also shifts the oxyhemoglobin dissociation curve to the right .

Carbon dioxide is a powerful respiratory stimulant. In fact, for each mm Hg rise of Pa CO_2 above baseline, normal awake subjects increase their minute ventilation by about 2–3 L/min. General anesthesia markedly decreases this response, and paralysis eliminates it. Finally, severe hypercapnia can produce hypoxia by displacement of oxygen from alveoli .

SUGGESTED READING

Dobson MB: Anaesthesia for diffi cult locations—developing countries and military confl icts. In: *International Practice of Anaesthesia* . Prys-Roberts C, Brown BR (editors). Butterworth Heinemann, 1996. Dorsch JA, Dorsch SE: *Understanding Anesthesia Equipment* , 5th ed. Lippincott, Williams & Wilkins, 2008.

CHAPTER

44

The Anesthesia Machine

KEY CONCEPTS

Misuse of anesthesia gas delivery systems is three times more likely than failure of the device to cause equipment-related adverse outcomes. An operator's lack of familiarity with the equipment or a failure to check machine function, or both, are the most frequent causes. These mishaps account for only about 2% of cases in the ASA Closed Claims Project database. The breathing circuit was the most common single source of injury (39%); nearly all damaging events were related to misconnects or disconnects. The anesthesia machine receives medical gases from a gas supply, controls the flow and reduces the pressure of desired gases to a safe level, vaporizes volatile anesthetics into the final gas mixture, and delivers the gases to a breathing circuit that is connected to the patient's airway. A mechanical ventilator attaches to the breathing circuit but can be excluded with a switch during spontaneous or manual (bag) ventilation. Whereas the oxygen supply can pass directly to its flow control valve, nitrous oxide, air, and other gases must first pass through safety devices before reaching their respective flow control valves. These devices permit the flow of other gases only if there is sufficient oxygen pressure in the safety device and help prevent accidental delivery of a hypoxic mixture in the event of oxygen supply failure.

4 Another safety feature of anesthesia machines is a linkage of the nitrous oxide gas flow to the oxygen gas flow; this arrangement helps ensure a minimum oxygen concentration of 25%. All modern vaporizers are agent specific and temperature corrected, capable of

5 delivering a constant concentration of agent regardless of temperature changes or flow through the vaporizer. A rise in airway pressure may signal worsening pulmonary compliance, an increase in tidal volume, or an obstruction in the breathing circuit, tracheal tube, or the

6 patient's airway. A drop in pressure may indicate an improvement in compliance, a decrease in tidal volume, or a leak in the circuit.

7 Traditionally ventilators on anesthesia machines have a double-circuit system design and are pneumatically powered and electronically controlled. Newer machines also incorporate microprocessor control that relies on sophisticated pressure and flow sensors. Some anesthesia machines have ventilators that use a single-circuit piston design. The major advantage of a piston ventilator is its ability to deliver accurate tidal volumes to patients with very poor lung compliance and

8 to very small patients.

— Continued next page

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9 Whenever a ventilator is used "disconnect alarms" must be passively activated. Anesthesia workstations should have at least three disconnect alarms: low pressure, low exhaled tidal volume, and low exhaled carbon dioxide.

10 Because the ventilator's spill valve is closed during inspiration, fresh gas fl ow from the machine's common gas outlet normally contributes to the tidal volume delivered to the patient.

11 Use of the oxygen fl ush valve during the inspiratory cycle of a ventilator must be avoided because the ventilator spill valve will be closed and the adjustable pressurelimiting (APL) valve is excluded; the surge of oxygen (600–1200 mL/s) and circuit pressure will be transferred to the patient's lungs. Large discrepancies between the set and actual tidal volume are often observed

12 in the operating room during volumecontrolled ventilation. Causes include breathing circuit compliance, gas compression, ventilator–fresh gas fl ow coupling, and leaks in the anesthesia machine, the breathing circuit, or the patient's airway.

13 Waste-gas scavengers dispose of gases that have been vented from the breathing circuit by the APL valve and ventilator spill valve. Pollution of the operating room environment with anesthetic gases may pose a health hazard to surgical personnel. A routine inspection of anesthesia equipment before each use increases operator familiarity and confi rms proper functioning. The

14 U.S. Food and Drug Administration has made available a generic checkout procedure for anesthesia gas machines and breathing systems.

No piece of equipment is more intimately associated with the practice of anesthesiology than the anesthe- sia machine (**Figure 4–1**). On the most basic level, the anesthesiologist uses the anesthesia machine to con- trol the patient's ventilation and oxygen delivery and to administer inhalation anesthetics. Proper func- tioning of the machine is crucial for patient safety. Modern anesthesia machines have become very sophisticated, incorporating many built-in safety features and devices, monitors, and multiple micro- processors that can integrate and monitor all compo- nents. Additional monitors can be added externally and oft en still be fully integrated. Moreover, modu- lar machine designs allow a wide variety of confi gu- rations and features within the same product line. Th e term *anesthesia workstation* is therefore oft en used for modern anesthesia machines. Th ere are two major manufacturers of anesthesia machines in the United States, Datex-Ohmeda (GE Healthcare) and Dräger Medical. Other manufacturers (eg, Mindray) produce anesthesia delivery systems. Anesthesia providers should carefully review the operations manuals of the machines present in their clinical practice.

Much progress has been made in reducing the number of adverse outcomes arising from anesthetic gas delivery equipment, through redesign of equip-

ment and education. Misuse of anesthesia gas delivery systems is three times more likely than failure of the device to cause equipment-related adverse outcomes. Equipment misuse is character- ized as errors in preparation, maintenance, or deployment of a device. Preventable anesthetic mis- haps are frequently traced to an operator's lack of familiarity with the equipment or a failure to check machine function, or both. Th ese mishaps account for only about 2% of cases in the American Society of Anesthesiologists' (ASA) Closed Claims Project database. Th e breathing circuit was the most common single source of injury (39%); nearly all damaging events were related to misconnects or disconnects. A misconnect was defi ned as a

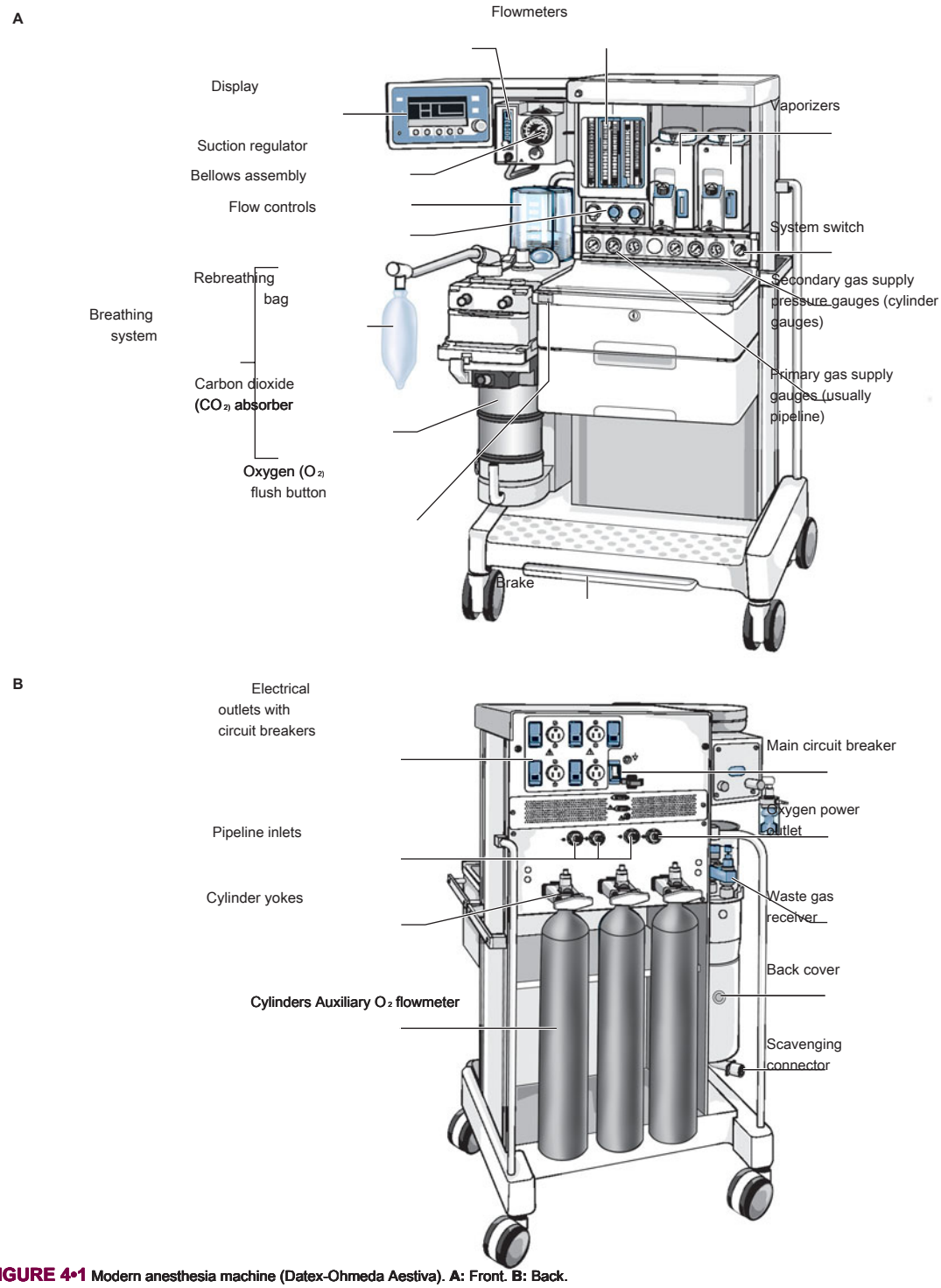

FIGURE 4•1 Modern anesthesia machine (Datex-Ohmeda Aestiva). **A:** Front. **B:** Back.

TABLE 4•1 Essential safety features on a modern anesthesia workstation.

Essential Features	Purpose
Noninterchangeable gas-specific connections to pipeline inlets (DISS)[1] with pressure gauges, filter, and check valve	Prevent incorrect pipeline attachments; detect failure, depletion, or fluctuation
Pin index safety system for cylinders with pressure gauges, and at least one oxygen cylinder	Prevent incorrect cylinder attachments; provide backup gas supply; detect depletion
Low oxygen pressure alarm	Detect oxygen supply failure at the common gas inlet
Minimum oxygen/nitrous oxide ratio controller device (hypoxic guard)	Prevent delivery of less than 21% oxygen
Oxygen failure safety device (shut-off or proportioning device)	Prevent administration of nitrous oxide or other gases when the oxygen supply fails
Oxygen must enter the common manifold downstream to other gases	Prevent hypoxia in event of proximal gas leak
Oxygen concentration monitor and alarm	Prevent administration of hypoxic gas mixtures in event of a low-pressure system leak; precisely regulate oxygen concentration
Automatically enabled essential alarms and monitors (eg, oxygen concentration)	Prevent use of the machine without essential monitors
Vaporizer interlock device	Prevent simultaneous administration of more than one volatile agent
Capnography and anesthetic gas measurement	Guide ventilation; prevent anesthetic overdose; help reduce awareness
Oxygen flush mechanism that does not pass through vaporizers	Rapidly refill or flush the breathing circuit
Breathing circuit pressure monitor and alarm	Prevent pulmonary barotrauma and detect sustained positive, high peak, and negative airway pressures
Exhaled volume monitor	Assess ventilation and prevent hypo- or hyperventilation
Pulse oximetry, blood pressure, and ECG monitoring	Provide minimal standard monitoring
Mechanical ventilator	Control alveolar ventilation more accurately and during muscle paralysis for prolonged periods
Backup battery	Provide temporary electrical power (>30 min) to monitors and alarms in event of power failure
Scavenger system	Prevent contamination of the operating room with waste anesthetic gases

[1] DISS, diameter-index safety system.

nonfunctional and unconventional confi guration of breathing circuit components or attachments. In decreasing frequency, other causes involved vapor- izers (21%), ventilators (17%), and oxygen supply (11%). Other more basic components of the anes- thesia machine (eg, valves) were responsible in only 7% of cases. All malpractice claims in the database that involved the anesthesia machine, oxygen supply tanks or lines, or ventilators occurred before 1990; since then claims involving breathing circuits and vaporizers have continued to occur.

Th e American National Standards Institute and subsequently the ASTM International (formerly the American Society for Testing and Materials, F1850–00) published standard specifi cations for anesthesia machines and their components. Table 4–1 lists essential features of a modern anesthesia work- station. Changes in equipment design have been directed at minimizing the probability of breath- ing circuit misconnects and disconnects and auto- mating machine checks. Because of the durability and functional longevity of anesthesia machines, the ASA has developed guidelines for determining anesthesia machine obsolescence (Table 4–2). Th is chapter is an introduction to anesthesia machine design, function, and use.

OVERVIEW

In its most basic form, the anesthesia machine receives medical gases from a gas supply, con- trols the fl ow and reduces the pressure of desired gases to a safe level, vaporizes volatile anesthetics into the fi nal gas mixture, and delivers the gases to a breathing circuit connected to the patient's airway (Figures 4–2 and 4–3). A mechanical ventilator attaches to the breathing circuit but can be excluded with a switch during spontaneous or manual (bag) ventilation. An auxiliary oxygen supply and suction regulator are also usually built into the workstation. In addition to standard safety features (Table 4–1) top-of-the-line anesthesia machines have additional safety features, enhancements, and built-in com- puter processors that integrate and monitor all com- ponents, perform automated machine checkouts,

TABLE 4•2 Unacceptable/undesirable features of older anesthesia machines. [1]

Unacceptable features
1. Flowmeter-controlled vaporizer (eg, copper kettle, Vernitrol)
2. More than one flow control valve for a single gas
3. Vaporizer with a rotary dial that increases concentration with clockwise rotation
4. Connections in the scavenging system that are the same size as breathing circuit connections
Undesirable features
1. Adjustable pressure-limiting (APL) valve that is not isolated during mechanical ventilation
2. Oxygen flow control knob that is not fluted or larger than other flow control knobs
3. Oxygen flush control that is unprotected from accidental activation
4. Lack of main On/Off switch for electrical power to integral monitors and alarms
5. Lack of antidisconnect device on the fresh gas hose (common gas outlet)
6. Lack of airway pressure alarms

[1] Data from ASA Guidelines for determining Anesthesia Machine Obsolescence.

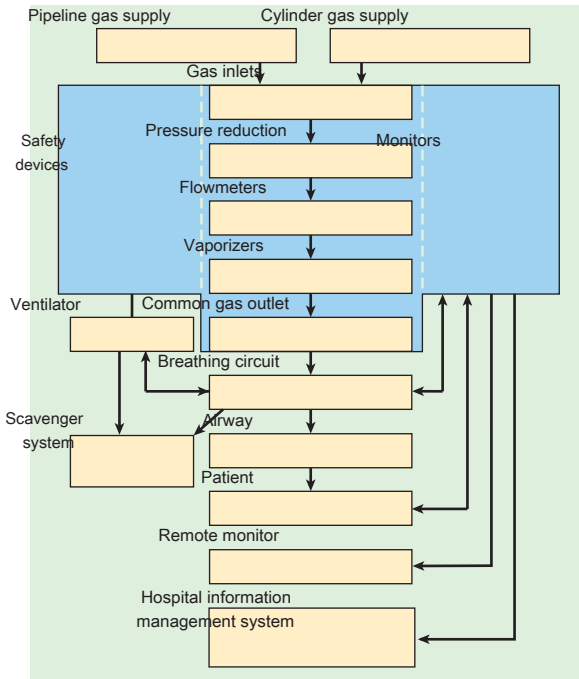

FIGURE 4•2 Functional schematic of an anesthesia machine/workstation.

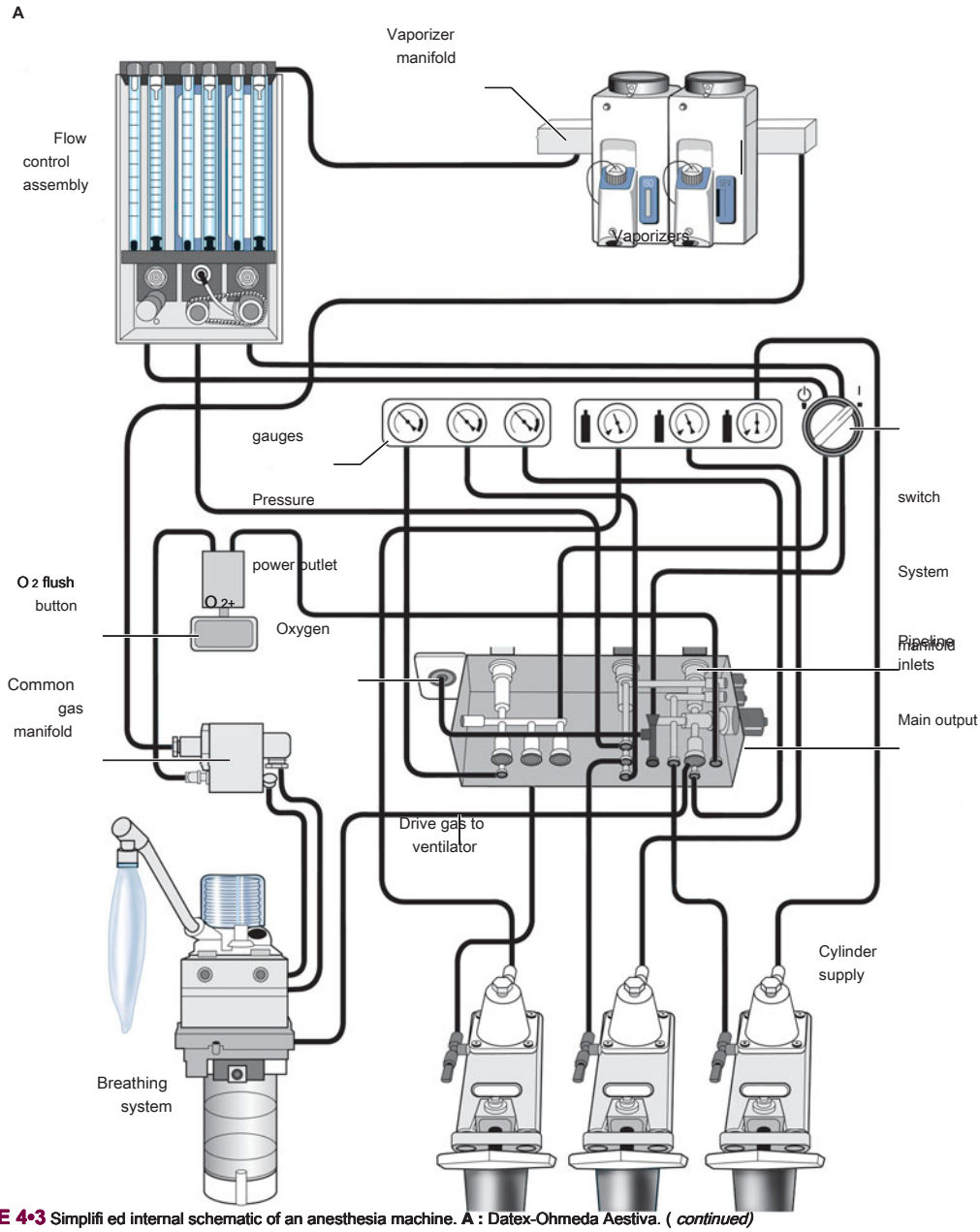

FIGURE 4•3 Simplifi ed internal schematic of an anesthesia machine. **A :** Datex-Ohmeda Aestiva. (*continued)*

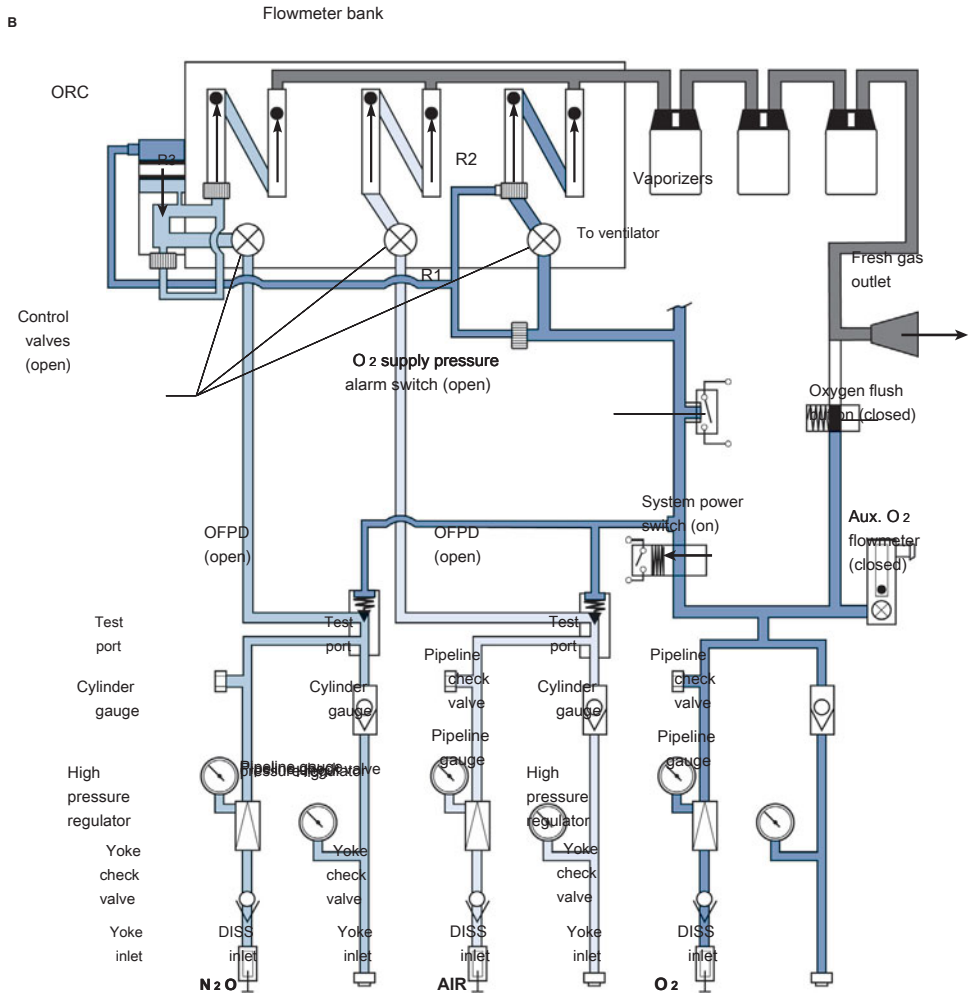

FIGURE 4•3 (*continued)* **B :** Dräger Narkomed. ORC, oxygen ratio controller.

and provide options such as automated record- keeping and networking external monitors and hospital information systems (Figure 4–4). Some machines are designed specifi cally for mobility, magnetic resonance imaging (MRI) compatibility or compactness.

GAS SUPPLY

Most machines have gas inlets for oxygen, nitrous oxide, and air. Compact models oft en lack air inlets, whereas other machines may have a fourth inlet for helium, heliox, carbon dioxide, or nitric oxide.

Separate inlets are provided for the primary pipeline gas supply that passes through the walls of health care facilities and the secondary cylinder gas sup- ply. Machines therefore have two gas inlet pressure gauges for each gas: one for pipeline pressure and another for cylinder pressure.

Pipeline Inlets

Oxygen and nitrous oxide (and oft en air) are deliv- ered from their central supply source to the operating room through a piping network. Th e tubing is color coded and connects to the anesthesia machine through a noninterchangeable **diameter-index**

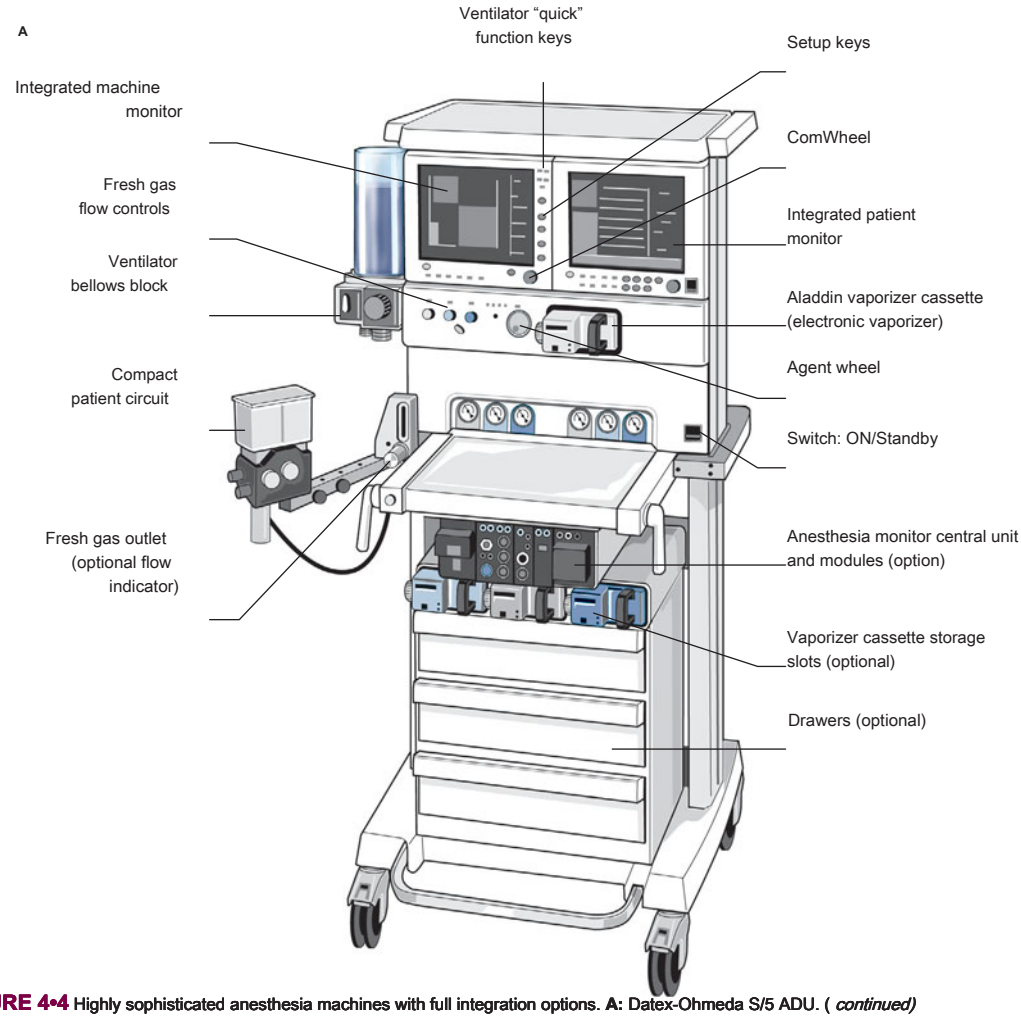

FIGURE 4•4 Highly sophisticated anesthesia machines with full integration options. **A:** Datex-Ohmeda S/5 ADU. (*continued)*

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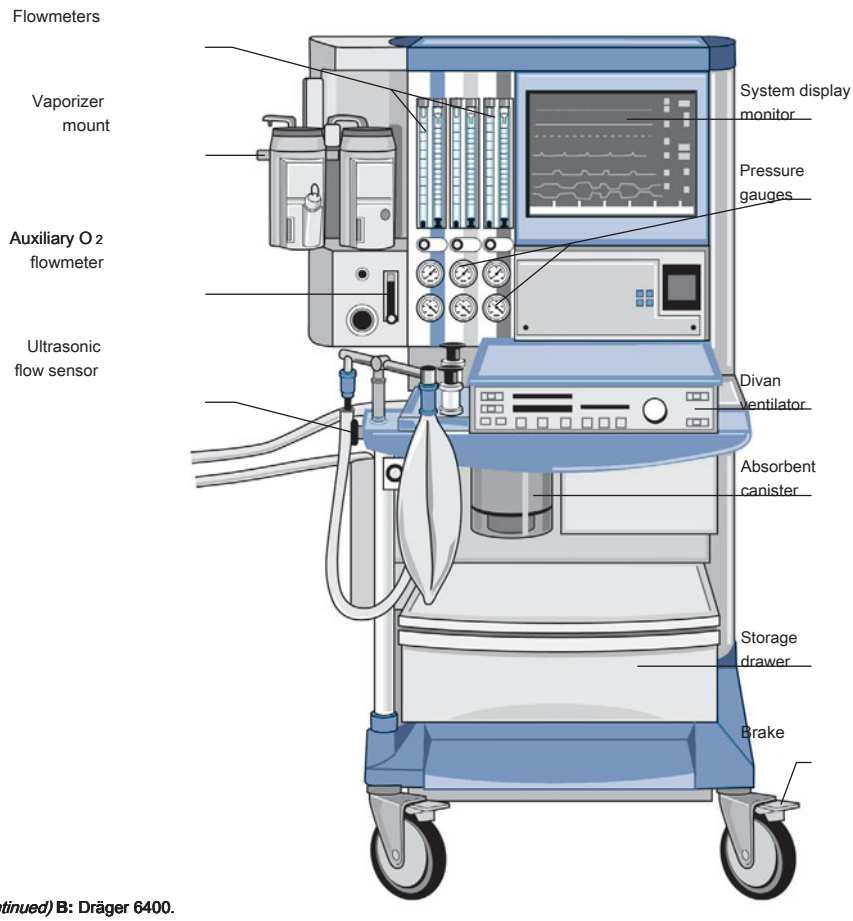

FIGURE 4•4 (*continued)* **B:** Dräger 6400.

safety system (DISS) fi tting that prevents incor- rect hose attachment. Th e noninterchangeability is achieved by making the bore diameter of the body and that of the connection nipple specifi c for each supplied gas. A fi lter helps trap debris from the wall supply and a one-way check valve prevents ret- rograde fl ow of gases into the pipeline supplies. It should be noted that most modern machines have an oxygen (pneumatic) power outlet that may be used to drive the ventilator or provide an auxiliary oxygen fl owmeter. Th e DISS fi ttings for the oxygen inlet and the oxygen power outlet are identical and should not be mistakenly interchanged. Th e approx- imate pipeline pressure of gases delivered to the anesthesia machine is 50 psig.

Cylinder Inlets

Cylinders attach to the machine via hanger-yoke assemblies that utilize a **pin index safety system** to prevent accidental connection of a wrong gas cylinder. Th e yoke assembly includes index pins, a washer, a gas fi lter, and a check valve that prevents retrograde gas fl ow. Th e gas cylinders are also color- coded for specifi c gases to allow for easy identifi ca- tion. In North America the following color-coding scheme is used: oxygen = green, nitrous oxide = blue, carbon dioxide = gray, air = yellow, helium = brown, nitrogen = black. In the United Kingdom, white is used for oxygen and black and white for air. Th e E-cylinders attached to the anesthesia machine are

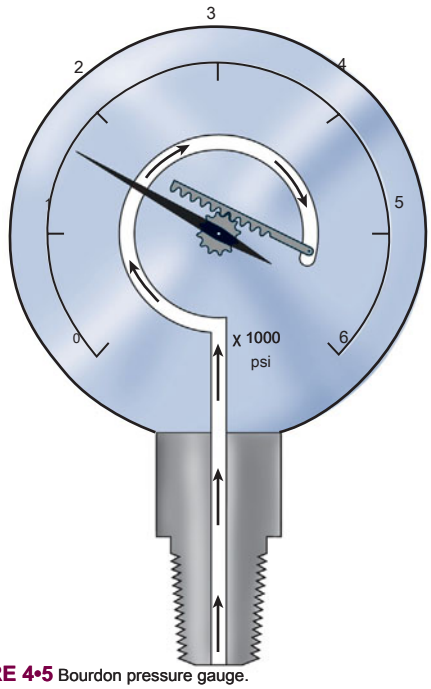

FIGURE 4•5 Bourdon pressure gauge.

a high-pressure source of medical gases and are generally used only as a back-up supply in case of pipeline failure. Pressure of gas supplied from the cylinder to the anesthesia machine is 45 psig. Some machines have two oxygen cylinders so that one cylinder can be used while the other is changed. At 20°C, a full cylinder contains 600 L of oxygen at a pressure of 1900 psig, and 1590 L of nitrous oxide at 745 psig. Cylinder pressure is usually measured by a Bourdon pressure gauge (Figure 4–5). A flexible tube within this gauge straightens when exposed to gas pressure, causing a gear mechanism to move a needle pointer.

FLOW CONTROL CIRCUITS

Pressure Regulators

Unlike the relatively constant pressure of the pipe- line gas supply, the high and variable gas pres- sure in cylinders makes flow control difficult and potentially dangerous. To enhance safety and ensure optimal use of cylinder gases, machines uti- lize a pressure regulator to reduce the cylinder gas pressure to 45–47 psig[1] before it enters the flow valve (Figure 4–6). This pressure, which is slightly lower than the pipeline supply, allows preferential use of the pipeline supply if a cylinder is left open (unless pipeline pressure drops below 45 psig). After pass- ing through Bourdon pressure gauges and check valves, the pipeline gases share a common pathway with the cylinder gases. A high-pressure relief valve provided for each gas is set to open when the sup- ply pressure exceeds the machine's maximum safety limit (95–110 psig), as might happen with a regula- tor failure on a cylinder. Some machines also use a second regulator to drop both pipeline and cylinder pressure further (two-stage pressure regulation). A second-stage pressure reduction may also be needed for an auxiliary oxygen flowmeter, the oxygen flush mechanism, or the drive gas to power a pneumatic ventilator.

Oxygen Supply Failure Protection Devices

Whereas the oxygen supply can pass directly to its flow control valve, nitrous oxide, air (in some machines), and other gases must first pass through safety devices before reaching their respective flow control valves. In other machines, air passes directly to its flow control valve; this allows administration of air even in the absence of oxygen. These devices per- mit the flow of other gases only if there is sufficient oxygen pressure in the safety device and help prevent accidental delivery of a hypoxic mixture in the event of oxygen supply failure. Thus in addition to supply- ing the oxygen flow control valve, oxygen from the common inlet pathway is used to pressurize safety devices, oxygen flush valves, and ventilator power outlets (in some models). Safety devices sense oxygen pressure via a small "piloting pressure" line that may be derived from the gas inlet or secondary regula- tor. In some anesthesia machine designs (eg, Datex- Ohmeda Excel), if the piloting pressure line falls below a threshold (eg, 20 psig), the shut-off valves close, preventing the administration of any other gases. The terms *fail-safe* and *nitrous cut-off* were pre- viously used for the nitrous oxide shut-off valve.

[1] Pressure unit conversions: 1 kiloPascal (kP) = kg/m · s^2 = 1000 N/m^2 = 0.01 bar = 0.1013 atmospheres = 0.145 psig = 10.2 cm H_2O = 7.5 mm Hg.

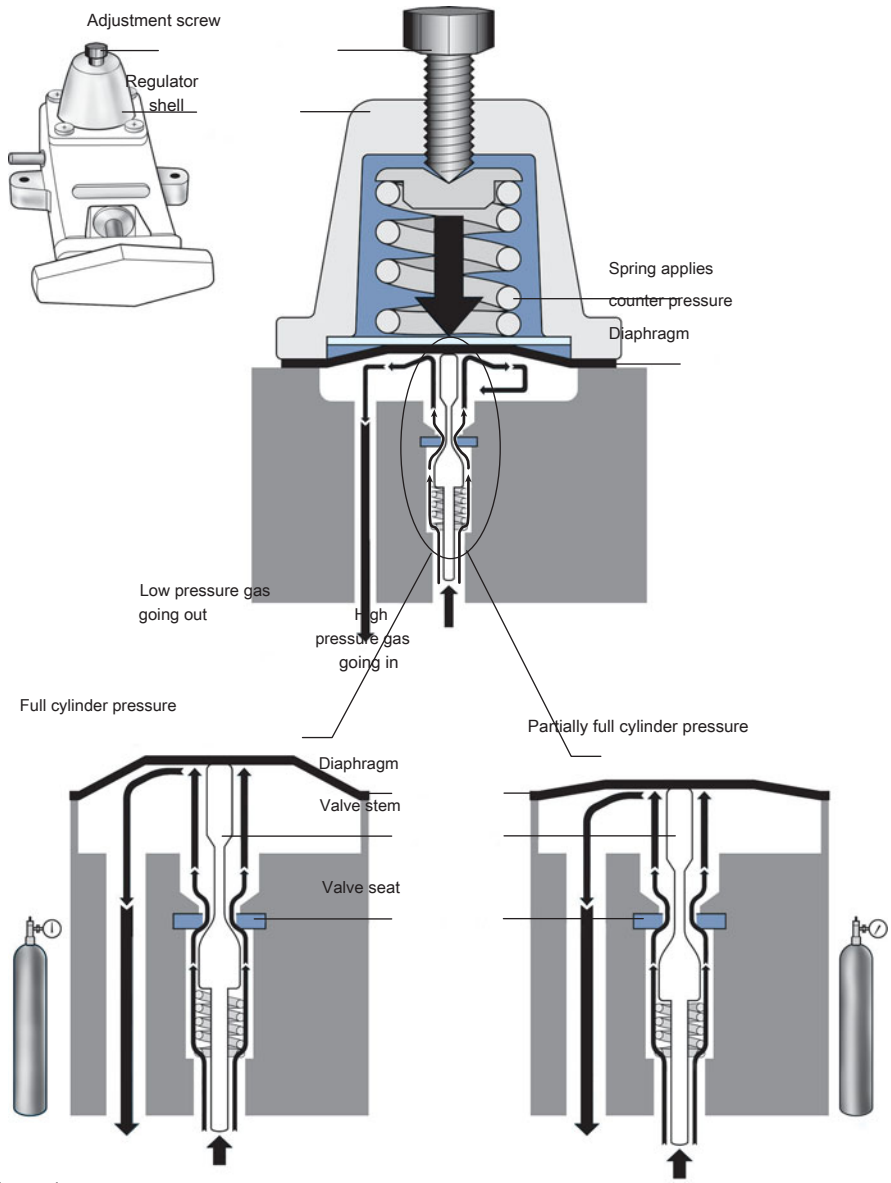

FIGURE 4•6 Cylinder inlet regulator.

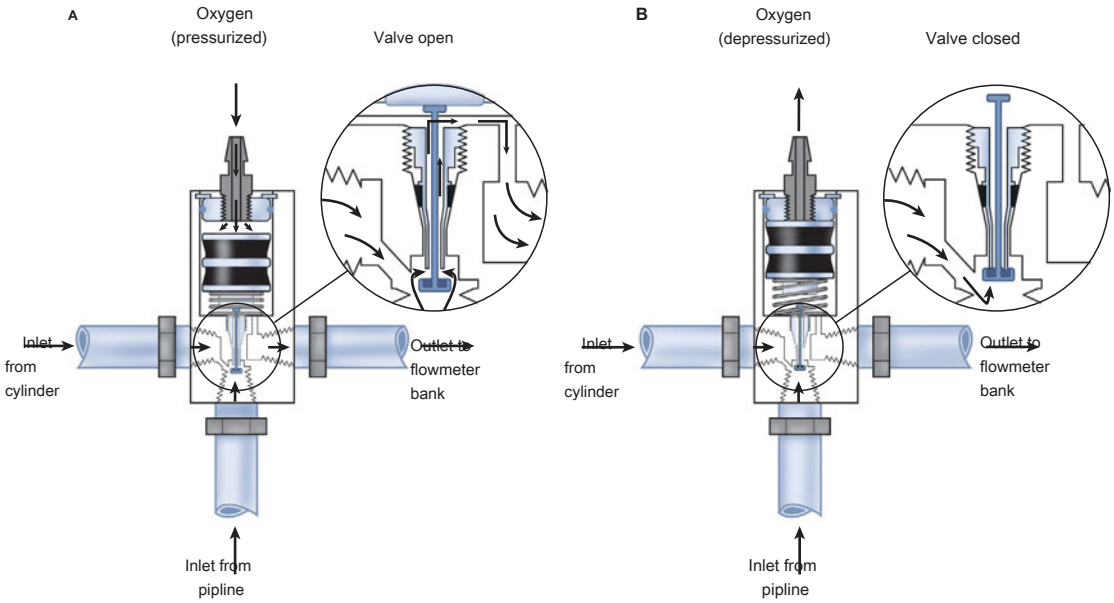

FIGURE 4•7 Dräger oxygen failure protection device (OFPD). **A:** Open. **B:** Closed.

Most modern (particularly Datex-Ohmeda) machines use a proportioning safety device instead of a threshold shut-off valve. Th ese devices, called either an oxygen failure protection device (Dräger) or a balance regulator (Datex-Ohmeda), propor- tionately reduce the pressure of nitrous oxide and other gases except for air (Figures 4–7 and 4–8).

Th ey completely shut off nitrous oxide and other gas fl ow only below a set minimum oxygen pressure (eg, 0.5 psig for nitrous oxide and 10 psig for other gases).

All machines also have an oxygen supply low- pressure sensor that activates alarm sounds when inlet gas pressure drops below a threshold value (usu- ally 20–30 psig). It must be emphasized that these safety devices do *not* protect against other possible causes of hypoxic accidents (eg, gas line misconnec- tions), in which threshold pressure may be main- tained by gases containing inadequate or no oxygen.

Flow Valves & Meters

Once the pressure has been reduced to a safe level, each gas must pass through fl ow control valves and is measured by fl owmeters before mixing with other gases, entering the active vaporizer, and exiting the machine's common gas outlet. **Gas lines proximal to fl ow valves are considered to be in the high- pressure circuit whereas those between the fl ow valves and the common gas outlet are considered part of the low-pressure circuit of the machine.**

When the knob of the fl ow control valve is turned counterclockwise, a needle valve is disengaged from its seat, allowing gas to fl ow through the valve (Figure 4–9). Stops in the full-off and full-on posi- tions prevent valve damage. Touch- and color-coded control knobs make it more diffi cult to turn the wrong gas off or on. As a safety feature the oxygen knob is usually fl uted, larger, and protrudes farther than the other knobs. Th e oxygen fl owmeter is positioned furthest to the right, downstream to the other gases; this arrangement helps to prevent hypoxia if there is leakage from a fl owmeter positioned upstream.

Flow control knobs control gas entry into the fl owmeters by adjustment via a needle valve. Flowmeters on anesthesia machines are classifi ed as either constant-pressure variable-orifi ce (rotameter) or electronic. In constant-pressure variable-orifi ce fl owmeters, an indicator ball, bobbin, or fl oat is sup- ported by the fl ow of gas through a tube (Th orpe

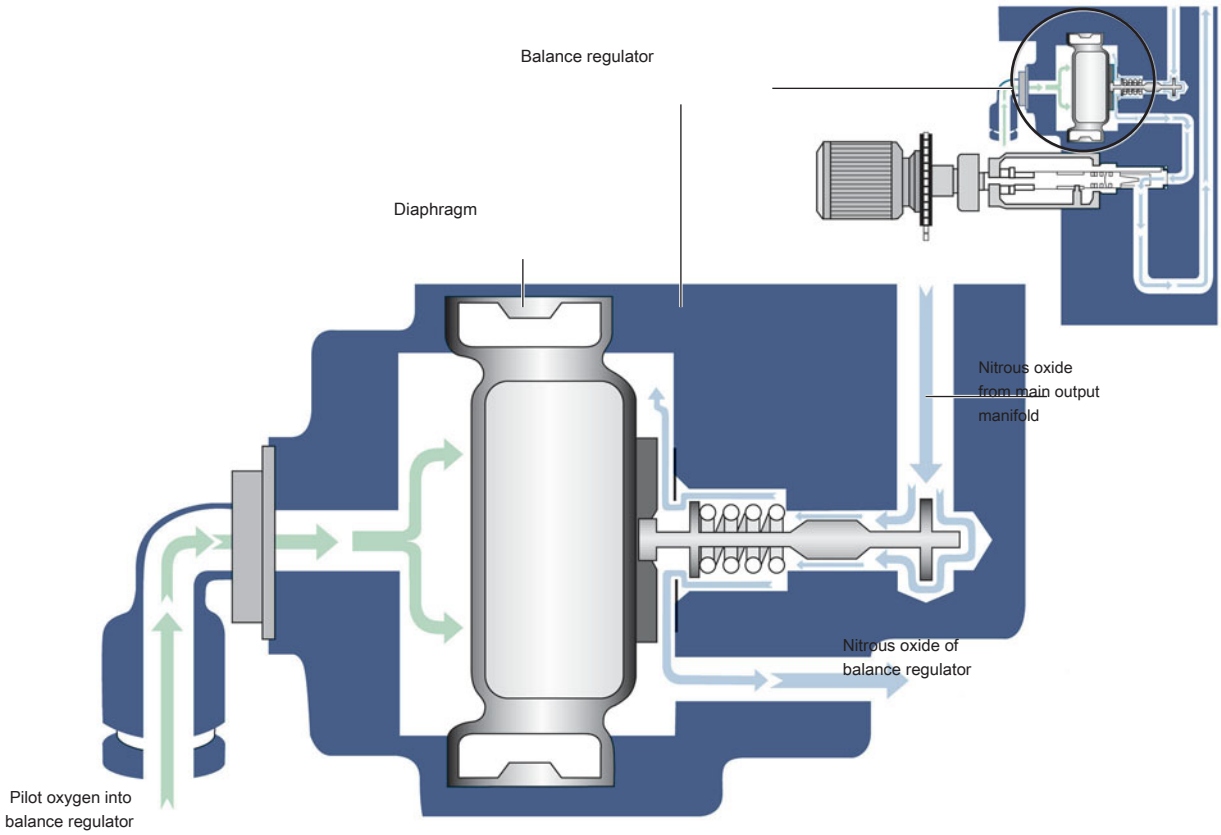

FIGURE 4•8 Datex-Ohmeda balance regulator.

tube) whose bore (orifi ce) is tapered. Near the bot- tom of the tube, where the diameter is small, a low fl ow of gas will create suffi cient pressure under the fl oat to raise it in the tube. As the fl oat rises, the (variable) orifi ce of the tube widens, allowing more gas to pass around the fl oat. Th e fl oat will stop rising when its weight is just supported by the diff erence in pressure above and below it. If fl ow is increased, the pressure under the fl oat increases, raising it higher in the tube until the pressure drop again just sup- ports the fl oat's weight. Th is pressure drop is con- stant regardless of the fl ow rate or the position in the tube and depends on the fl oat weight and tube cross-sectional area.

Flowmeters are calibrated for specifi c gases, as the fl ow rate across a constriction depends on the gas's viscosity at low laminar fl ows (Poiseuille's law) and its density at high turbulent fl ows. To minimize the eff ect of friction between them and the tube's wall, fl oats are designed to rotate constantly, which keeps them centered in the tube. Coating the tube's interior with a conductive substance grounds the system and reduces the eff ect of static electricity. Some fl owmeters have two glass tubes, one for low fl ows and another for high fl ows (Figure 4–10A);

the two tubes are in series and are still controlled by one valve. A dual taper design can allow a sin- gle fl owmeter to read both high and low fl ows (Figure 4–10B). **Causes of fl owmeter malfunction include debris in the fl ow tube, vertical tube mis- alignment, and sticking or concealment of a fl oat at the top of a tube.**

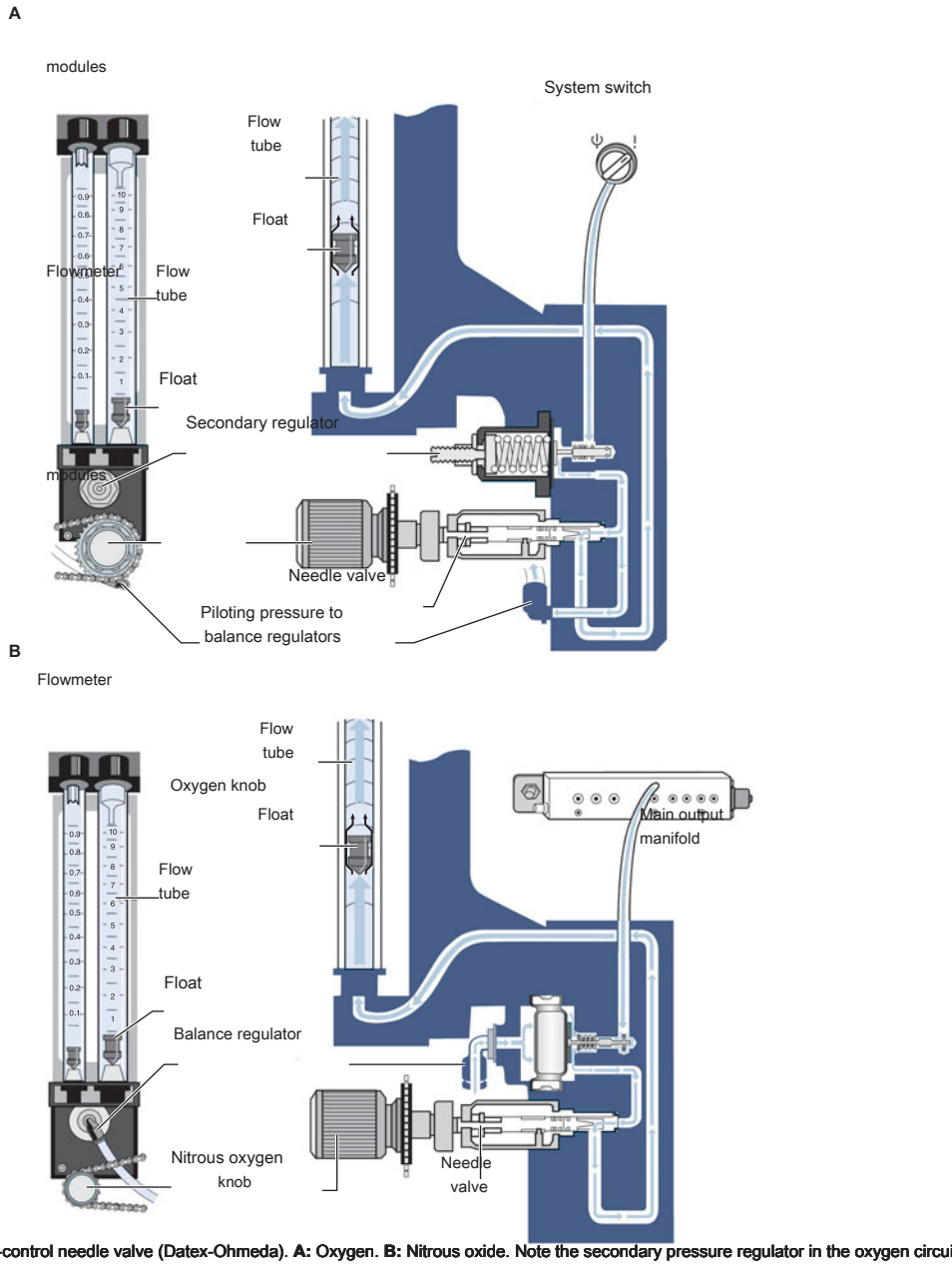

FIGURE 4•9 Gas fl ow-control needle valve (Datex-Ohmeda). **A:** Oxygen. **B:** Nitrous oxide. Note the secondary pressure regulator in the oxygen circuit and the balance regulator in the nitrous oxide circuit.

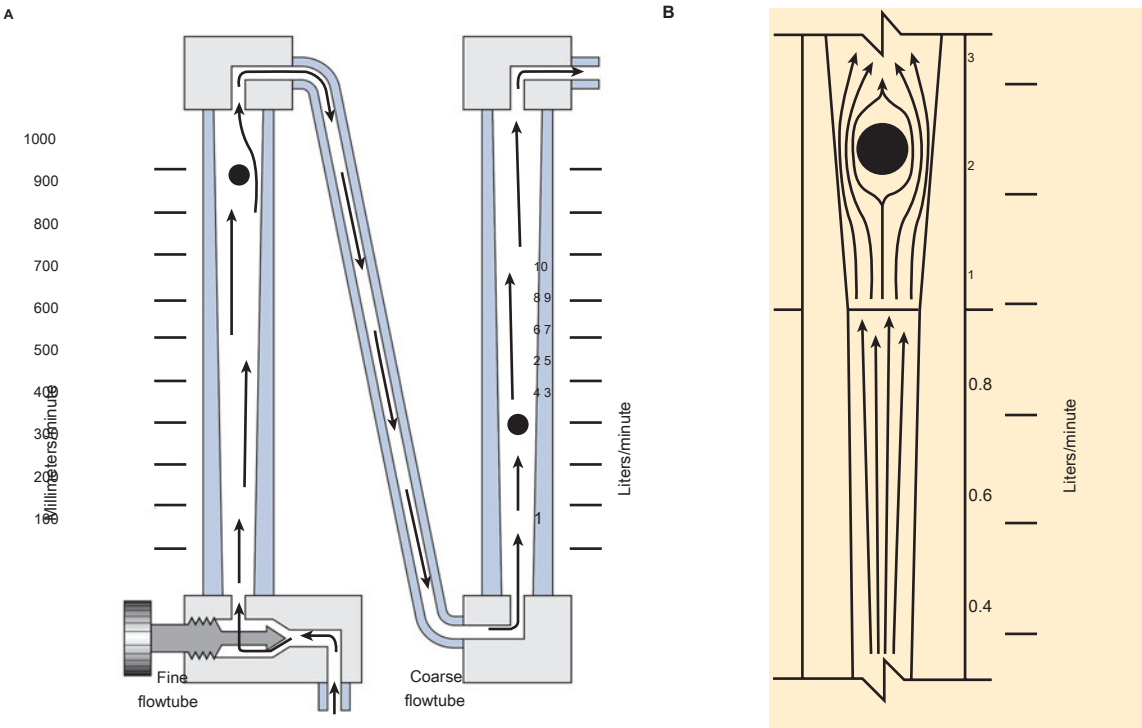

FIGURE 4•10 Constant-pressure variable orifi ce fl owmeters (Thorpe type). **A:** Two tube design. **B:** Dual taper design.

Should a leak develop within or downstream from an oxygen fl owmeter, a hypoxic gas mixture can be delivered to the patient (Figure 4–11). To reduce this risk, oxygen fl owmeters are *always* posi- tioned downstream to all other fl owmeters (nearest to the vaporizer).

Some anesthesia machines have electronic fl ow control and measurement (Figure 4–12). In such instances, a back-up conventional (Th orpe) auxil- iary oxygen fl owmeter is provided. Other models have conventional fl owmeters but electronic measurement of gas fl ow along with Th orpe tubes and

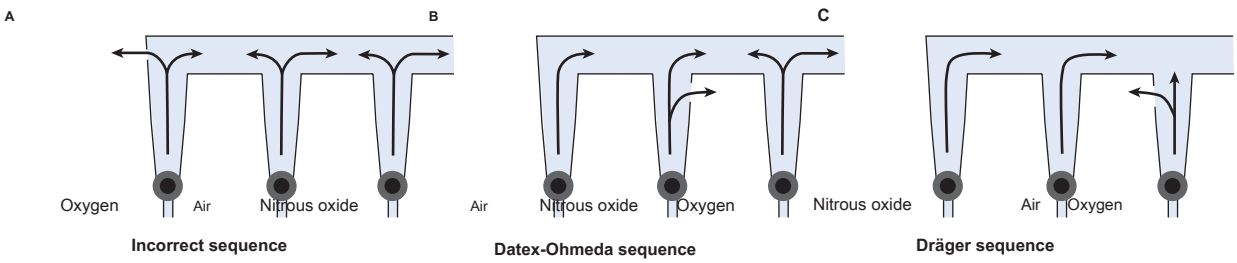

FIGURE 4•11 Sequence of fl owmeters in a three-gas machine. **A:** An unsafe sequence. **B:** Typical Datex Ohmeda sequence. **C:** Typical Dräger sequence. Note that regardless of sequence a leak in the oxygen tube or further downstream can result in delivery of a hypoxic mixture.

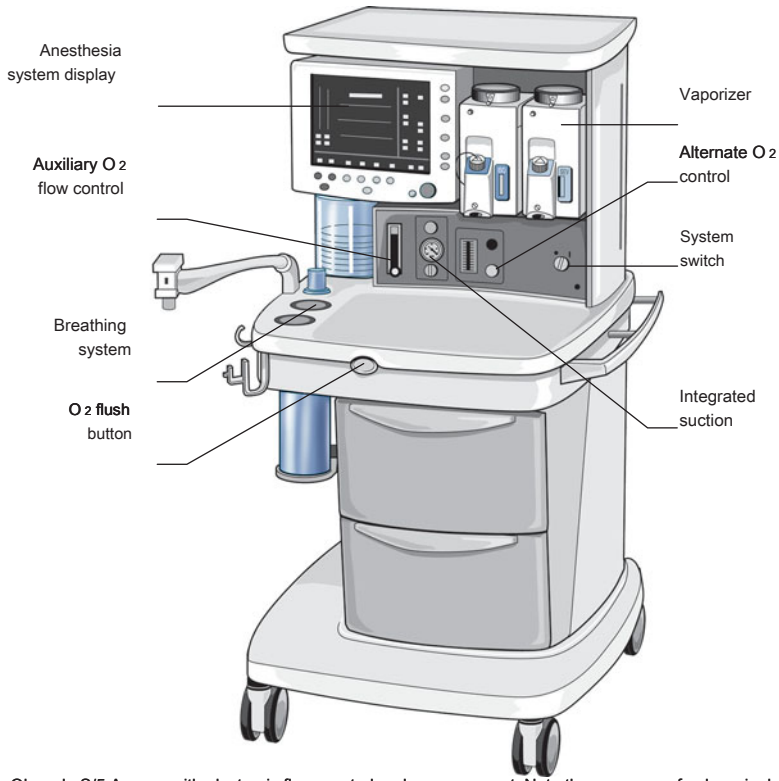

FIGURE 4•12 Datex-Ohmeda S/5 Avance with electronic fl ow control and measurement. Note the presence of only a single alternate fl owmeter for oxygen to be used in a power failure.

digital or digital/graphic displays (Figure 4–13). Th e amount of pressure drop caused by a fl ow restrictor is the basis for measurement of gas fl ow rate in these systems. In these machines oxygen, nitrous oxide, and air each have a separate electronic fl ow mea- surement device in the fl ow control section before they are mixed together. Electronic fl owmeters are essential components in workstations if gas fl ow rate data will be acquired automatically by computerized anesthesia recording systems.

A. Minimum Oxygen Flow

Th e oxygen fl ow valves are usually designed to deliver a minimum fl ow of 150 mL/min when the anesthe- sia machine is turned on. One method involves the use of a minimum fl ow resistor (Figure 4–14). Th is safety feature helps ensure that some oxygen enters the breathing circuit even if the operator forgets to turn on the oxygen fl ow. Some machines are designed to deliver minimum fl ow or low-fl ow anes- thesia (<1 L/min) and have minimum oxygen fl ows as low as 50 mL/min.

B. Oxygen/Nitrous Oxide Ratio Controller

Another safety feature of anesthesia machines is a linkage of the nitrous oxide gas fl ow to the oxygen gas fl ow; this arrangement helps ensure a minimum oxygen concentration of 25%. Th e oxy- gen/nitrous oxide ratio controller links the two fl ow valves either pneumatically or mechanically. To maintain the minimum oxygen concentration, the system (Link-25) in Datex-Ohmeda machines increases the fl ow of oxygen, whereas the oxy- gen ratio monitor controller (ORMC) in Dräger machines reduces the concentration of nitrous oxide. It should be noted that this safety device does

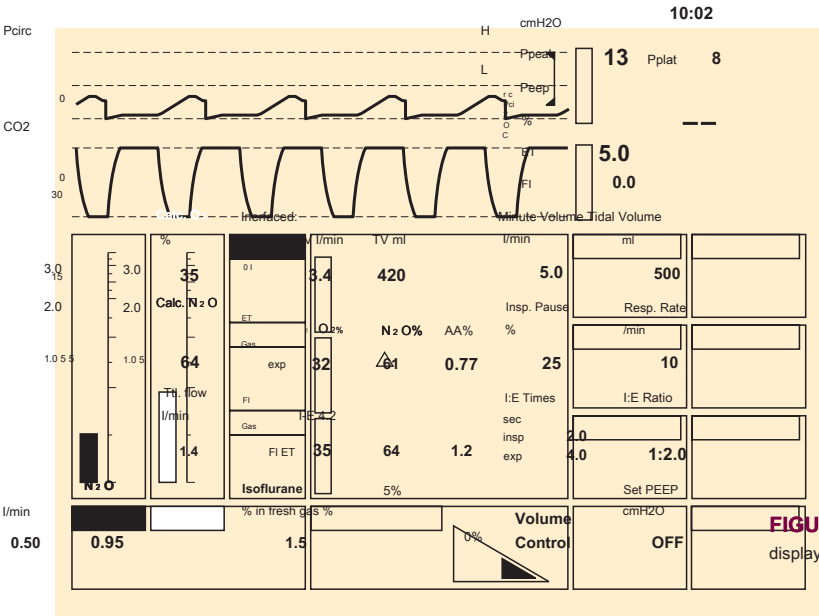

FIGURE 4•13 Graphic and digital fl owmeter display of Datex-Ohmeda S/5 ADU.

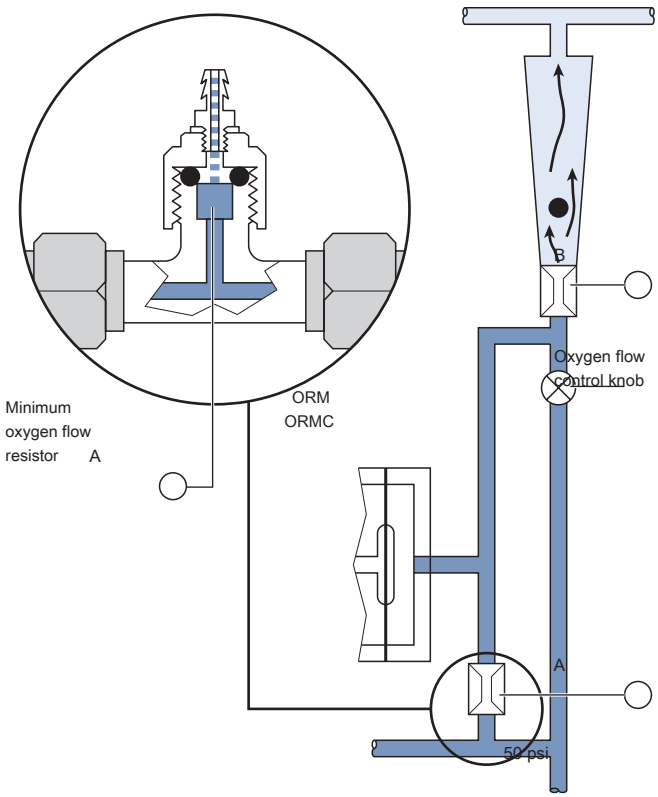

FIGURE 4•14 A bypass tube with minimum fl ow resistor upstream before the oxygen fl ow control valve ensures minimum oxygen fl ow even when the needle valve is turned off . A, B, resistors.

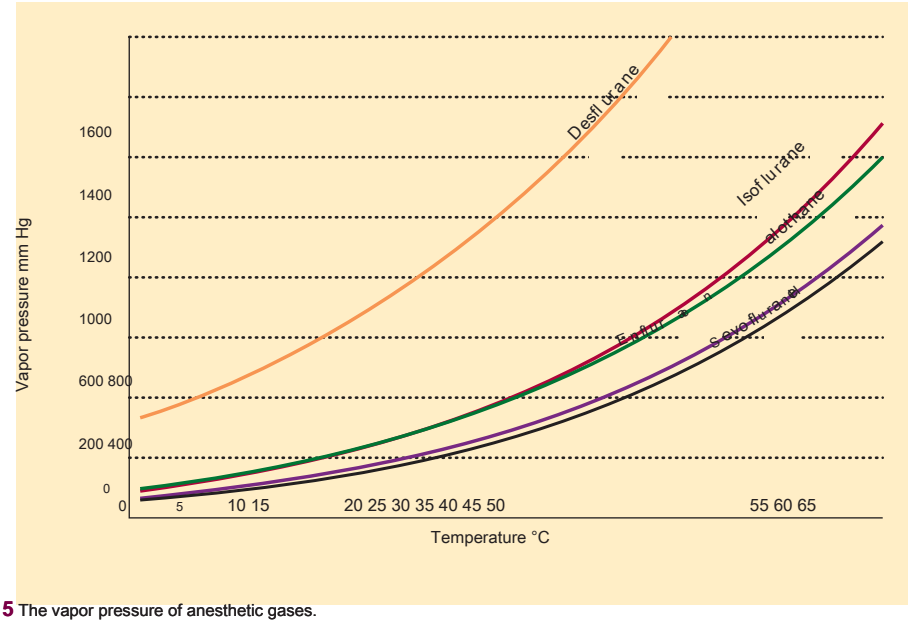

FIGURE 4•15 The vapor pressure of anesthetic gases.

not aff ect the fl ow of a third gas (eg, air, helium, or carbon dioxide).

Vaporizers

Volatile anesthetics (eg, halothane, isofl urane, des- fl urane, sevofl urane) must be vaporized before being delivered to the patient. Vaporizers have concen- tration-calibrated dials that precisely add volatile anesthetic agents to the combined gas fl ow from all fl owmeters. Th ey must be located between the fl ow- meters and the common gas outlet. Moreover, unless the machine accepts only one vaporizer at a time, all anesthesia machines should have an interlocking or exclusion device that prevents the concurrent use of more than one vaporizer.

A. Physics of Vaporization

At temperatures encountered in the operating room, the molecules of a volatile anesthetic in a closed con- tainer are distributed between the liquid and gaseous phases. Th e gas molecules bombard the walls of the container, creating the saturated vapor pressure of that agent. Vapor pressure depends on the character- istics of the volatile agent and the temperature. Th e greater the temperature, the greater the tendency for the liquid molecules to escape into the gaseous phase and the greater the vapor pressure (Figure 4–15).

Vaporization requires energy (the latent heat of vaporization), which results in a loss of heat from the liquid. As vaporization proceeds, temperature of the remaining liquid anesthetic drops and vapor pres- sure decreases unless heat is readily available to enter the system. Vaporizers contain a chamber in which a carrier gas becomes saturated with the volatile agent.

A liquid's boiling point is the temperature at which its vapor pressure is equal to the atmospheric pressure. As the atmospheric pressure decreases (as in higher altitudes), the boiling point also decreases. Anesthetic agents with low boiling points are more susceptible to variations in barometric pressure than agents with higher boiling points. Among the com- monly used agents, desfl urane has the lowest boiling point (22.8°C at 760 mm Hg).

B. Copper Kettle

Th e copper kettle vaporizer is no longer used in clini- cal anesthesia; however, understanding how it works provides invaluable insight into the delivery of vola- tile anesthetics (Figure 4–16). It is classifi ed as a measured-fl ow vaporizer (or fl owmeter- controlled

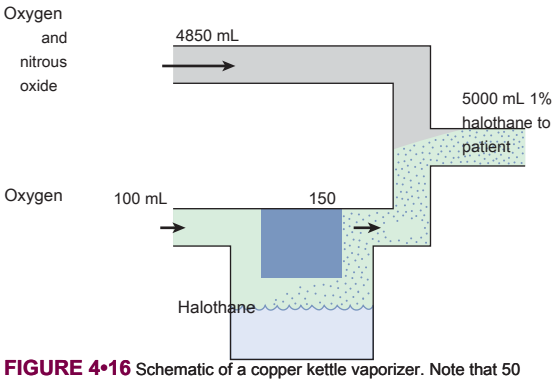

FIGURE 4•16 Schematic of a copper kettle vaporizer. Note that 50 mL/min of halothane vapor is added for each 100 mL/min oxygen fl ow that passes through the vaporizer.

vaporizer). In a copper kettle, the amount of carrier gas bubbled through the volatile anesthetic is con- trolled by a dedicated fl owmeter. Th is valve is turned off when the vaporizer circuit is not in use. Copper is used as the construction metal because its relatively high specifi c heat (the quantity of heat required to raise the temperature of 1 g of substance by 1°C) and high thermal conductivity (the speed of heat con- ductance through a substance) enhance the vapor- izer's ability to maintain a constant temperature. All the gas entering the vaporizer passes through the anesthetic liquid and becomes saturated with vapor. One milliliter of liquid anesthetic is the equivalent of approximately 200 mL of anesthetic vapor. Because the vapor pressure of volatile anesthetics is greater than the partial pressure required for anesthesia, the saturated gas leaving a copper kettle has to be diluted before it reaches the patient.

For example, the vapor pressure of halothane is 243 mm Hg at 20°C, so the concentration of halo- thane exiting a copper kettle at 1 atmosphere would be 243/760, or 32%. If 100 mL of oxygen enters the kettle, roughly 150 mL of gas exits (the initial 100 mL of oxygen plus 50 mL of saturated halo- thane vapor), one-third of which would be saturated halothane vapor. To deliver a 1% concentration of halothane (MAC 0.75%), the 50 mL of halothane vapor and 100 mL of carrier gas that left the copper kettle have to be diluted within a total of 5000 mL of fresh gas fl ow. Th us, every 100 mL of oxygen passing through a halothane vaporizer translates into a 1% increase in concentration if total gas fl ow into the breathing circuit is 5 L/min. Th erefore when total fl ow is fi xed, fl ow through the vaporizer determines the ultimate concentration of anesthetic. Isofl urane has an almost identical vapor pressure, so the same relationship between copper kettle fl ow, total gas fl ow, and anesthetic concentration exists. However, if total gas fl ow changes without an adjustment in copper kettle fl ow (eg, exhaustion of a nitrous oxide cylinder), the delivered volatile anesthetic concen- tration rises rapidly to potentially dangerous levels.

C. Modern Conventional Vaporizers

All modern vaporizers are agent specifi c and temperature-corrected, capable of deliver- ing a constant concentration of agent regardless of temperature changes or fl ow through the vaporizer. Turning a single calibrated control knob counter- clockwise to the desired percentage diverts an appropriate small fraction of the total gas fl ow into the carrier gas, which fl ows over the liquid anes- thetic in a vaporizing chamber, leaving the balance to exit the vaporizer unchanged **(Figure 4–17).**

Because some of the entering gas is never exposed to anesthetic liquid, this type of agent-specifi c vapor- izer is also known as a variable-bypass vaporizer.

Temperature compensation is achieved by a strip composed of two diff erent metals welded together. Th e metal strips expand and contract dif- ferently in response to temperature changes. When the temperature decreases, diff erential contraction causes the strip to bend allowing more gas to pass through the vaporizer. Such bimetallic strips are also used in home thermostats. As the temperature rises diff erential expansion causes the strip to bend the other way restricting gas fl ow into the vaporizer. Altering total fresh gas fl ow rates within a wide range does not signifi cantly aff ect anesthetic concentration because the same proportion of gas is exposed to the liquid. However, the real output of an agent would be lower than the dial setting at extremely high fl ow (>15 L/min); the converse is true when the fl ow rate is less than 250 mL/min. Changing the gas composi- tion from 100% oxygen to 70% nitrous oxide may transiently decrease volatile anesthetic concentra- tion due to the greater solubility of nitrous oxide in volatile agents.

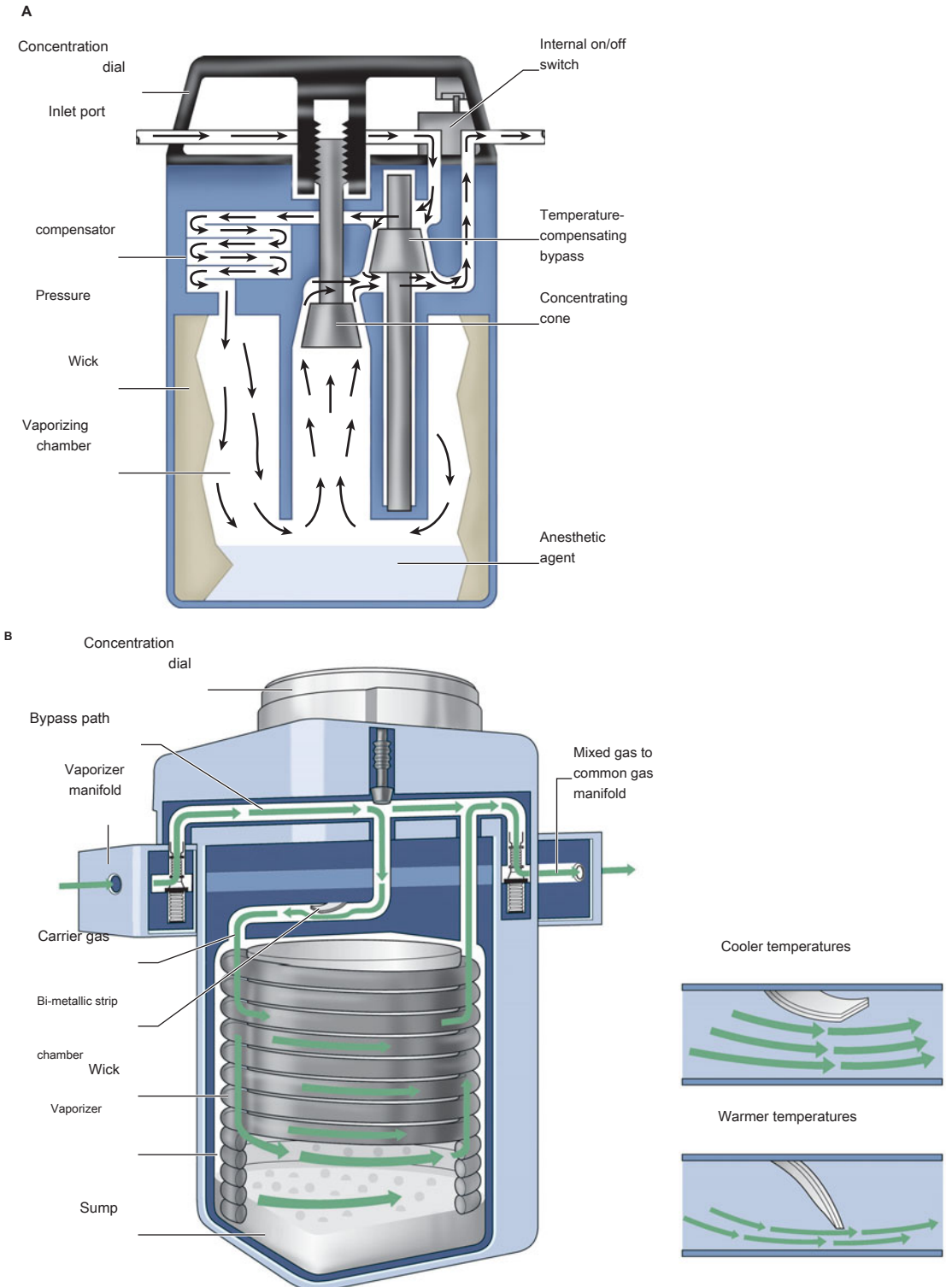

FIGURE 4•17 Schematic of agent-specifi c variable-bypass vaporizers. **A:** Dräger Vapor 19.n. **B:** Datex-Ohmeda Tec 7.

Given that these vaporizers are agent specifi c, fi lling them with the incorrect anesthetic should be avoided. For example, unintentionally fi lling a sevofl urane-specifi c vaporizer with halothane could lead to an anesthetic overdose. First, halothane's higher vapor pressure (243 mm Hg versus 157 mm Hg) will cause a 40% greater amount of anesthetic vapor to be released. Second, halothane is more than twice as potent as sevofl urane (MAC 0.75 versus.

2.0). Conversely, fi lling a halothane vaporizer with sevofl urane will cause an anesthetic underdosage. Modern vaporizers off er agent-specifi c keyed fi lling ports to prevent fi lling with an incorrect agent.

Excessive tilting of older vaporizers (Tec 4, Tec 5, and Vapor 19.n) during transport may fl ood the bypass area and lead to dangerously high anesthetic concentrations. In the event of tilting and spill- age, high fl ow of oxygen with the vaporizer turned off should be used to vaporize and fl ush the liquid anesthetic from the bypass area. Fluctuations in pressure from positive-pressure ventilation in older anesthesia machines may cause a transient reversal of fl ow through the vaporizer, unpredictably chang- ing agent delivery. Th is "pumping eff ect" is more pronounced with low gas fl ows. A one-way check valve between the vaporizers and the oxygen fl ush valve (Datex-Ohmeda) together with some design modifi cations in newer units limit the occurrence of some of these problems. Variable bypass vapor- izers compensate for changes in ambient pressures (ie, altitude changes maintaining relative anesthetic gas partial pressure).

D. Electronic Vaporizers

Electronically controlled vaporizers must be utilized for desfl urane and are used for all volatile anesthet- ics in some sophisticated anesthesia machines.

1. Desfl urane vaporizer — Desfl urane's vapor pres- sure is so high that at sea level it almost boils at room temperature (Figure 4–15). **Th is high vola- tility, coupled with a potency only one-fi ft h that of other volatile agents, presents unique delivery problems.** First, the vaporization required for gen- eral anesthesia produces a cooling eff ect that would overwhelm the ability of conventional vaporizers to maintain a constant temperature. Second, because it vaporizes so extensively, a tremendously high fresh gas fl ow would be necessary to dilute the carrier gas to clinically relevant concentrations. Th ese problems have been addressed by the development of special desfl urane vaporizers. A reservoir containing desfl u- rane (desfl urane sump) is electrically heated to 39°C (signifi cantly higher than its boiling point) creating a vapor pressure of 2 atmospheres. Unlike a variable- bypass vaporizer, no fresh gas fl ows through the des- fl urane sump. Rather, pure desfl urane vapor joins the fresh gas mixture before exiting the vaporizer. Th e amount of desfl urane vapor released from the sump depends on the concentration selected by turning the control dial and the fresh gas fl ow rate. Although the Tec 6 Plus maintains a constant desfl urane con- centration over a wide range of fresh gas fl ow rates, it cannot automatically compensate for changes in elevation. Decreased ambient pressure (eg, high elevation) does not aff ect the concentration of agent delivered, but decreases the partial pressure of the agent. Th us, at high elevations, the anesthesiologist must manually increase the concentration control.

2. Aladin cassette vaporizer — Th is vaporizer is designed for use with the Datex-Ohmeda S/5 ADU and Aisys machines. Gas fl ow from the fl ow con- trol is divided into bypass fl ow and liquid chamber fl ow (Figure 4–18). Th e latter is conducted into an agent-specifi c, color-coded, cassette (Aladin cassette) in which the volatile anesthetic is vaporized. Th e machine accepts only one cassette at a time and rec- ognizes the cassette through magnetic labeling. Th e cassette does not contain any bypass fl ow channels; therefore, unlike traditional vaporizers, liquid anes- thetic cannot escape during handling and the cassette can be carried in any position. Aft er leaving the cas- sette, the now anesthetic-saturated liquid chamber fl ow reunites with the bypass fl ow before exiting the fresh gas outlet. A fl ow restrictor valve near the bypass fl ow helps to adjust the amount of fresh gas that fl ows to the cassette. Adjusting the ratio between the bypass fl ow and liquid chamber fl ow changes the concentration of volatile anesthetic agent delivered to the patient. In practice, the clinician changes the con- centration by turning the agent wheel, which oper- ates a digital potentiometer. Soft ware sets the desired fresh gas agent concentration according to the num- ber of output pulses from the agent wheel. Sensors in the cassette measure pressure and temperature, thus determining agent concentration in the gas leaving the cassette. Correct liquid chamber fl ow is

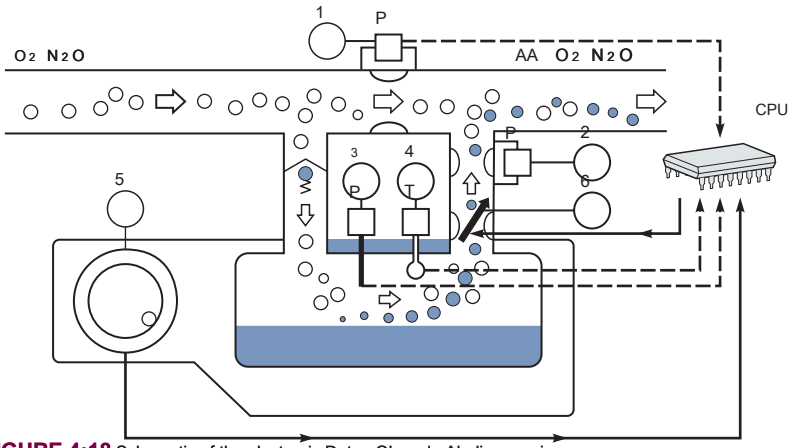

FIGURE 4•18 Schematic of the electronic Datex-Ohmeda Aladin vaporizer.

calculated based on desired fresh gas concentration and determined cassette gas concentration.

Common (Fresh) Gas Outlet

In contrast to the multiple gas inlets, the anesthesia machine has only one common gas outlet that sup- plies gas to the breathing circuit. Th e term *fresh gas outlet* is also oft en used because of its critical role in adding new gas of fi xed and known composition to the circle system. Unlike older models, some newer anesthesia machines measure and report common outlet gas fl ows (Datex-Ohmeda S/5 ADU and Narkomed 6400). An antidisconnect retaining device is used to prevent accidental detachment of the gas outlet hose that connects the machine to the breathing circuit.

Th e oxygen fl ush valve provides a high fl ow (35–75 L/min) of oxygen directly to the common gas outlet, bypassing the fl owmeters and vaporizers. It is used to rapidly refi ll or fl ush the breathing circuit, but because the oxygen may be supplied at a line pres- sure of 45–55 psig, there is a real potential of lung barotrauma. For this reason, the fl ush valve must be used cautiously whenever a patient is connected to the breathing circuit. Moreover, inappropriate use of the fl ush valve (or a situation of stuck valve) may result in backfl ow of gases into the low-pressure cir- cuit, causing dilution of inhaled anesthetic concen- tration. Some machines use a second-stage regulator to drop the oxygen fl ush pressure to a lower level.

A protective rim around the fl ush button limits the possibility of unintentional activation. Anesthesia machines (eg, Datex-Ohmeda Aestiva/5) may have an optional auxiliary common gas outlet that is acti- vated with a dedicated switch. It is primarily used for performing the low-pressure circuit leak test (see Anesthesia Machine Checkout List).

THE BREATHING CIRCUIT

Th e breathing system most commonly used with anesthesia machines is the circle system (Figure 4–19); a Bain circuit is occasionally used. Th e components and use of the circle system were previously discussed. It is important to note that gas composition at the common gas outlet can be controlled precisely and rapidly by adjustments in fl owmeters and vaporizers. In contrast, gas com- position, especially volatile anesthetic concentra- tion, in the breathing circuit is signifi cantly aff ected by other factors, including anesthetic uptake in the patient's lungs, minute ventilation, total fresh gas fl ow, volume of the breathing circuit, and the pres- ence of gas leaks. Use of high gas fl ow rates during induction and emergence decreases the eff ects of such variables and can diminish the magnitude of discrepancies between fresh gas outlet and circle system anesthetic concentrations. Measurement of inspired and expired anesthetic gas concentration also greatly facilitates anesthetic management.

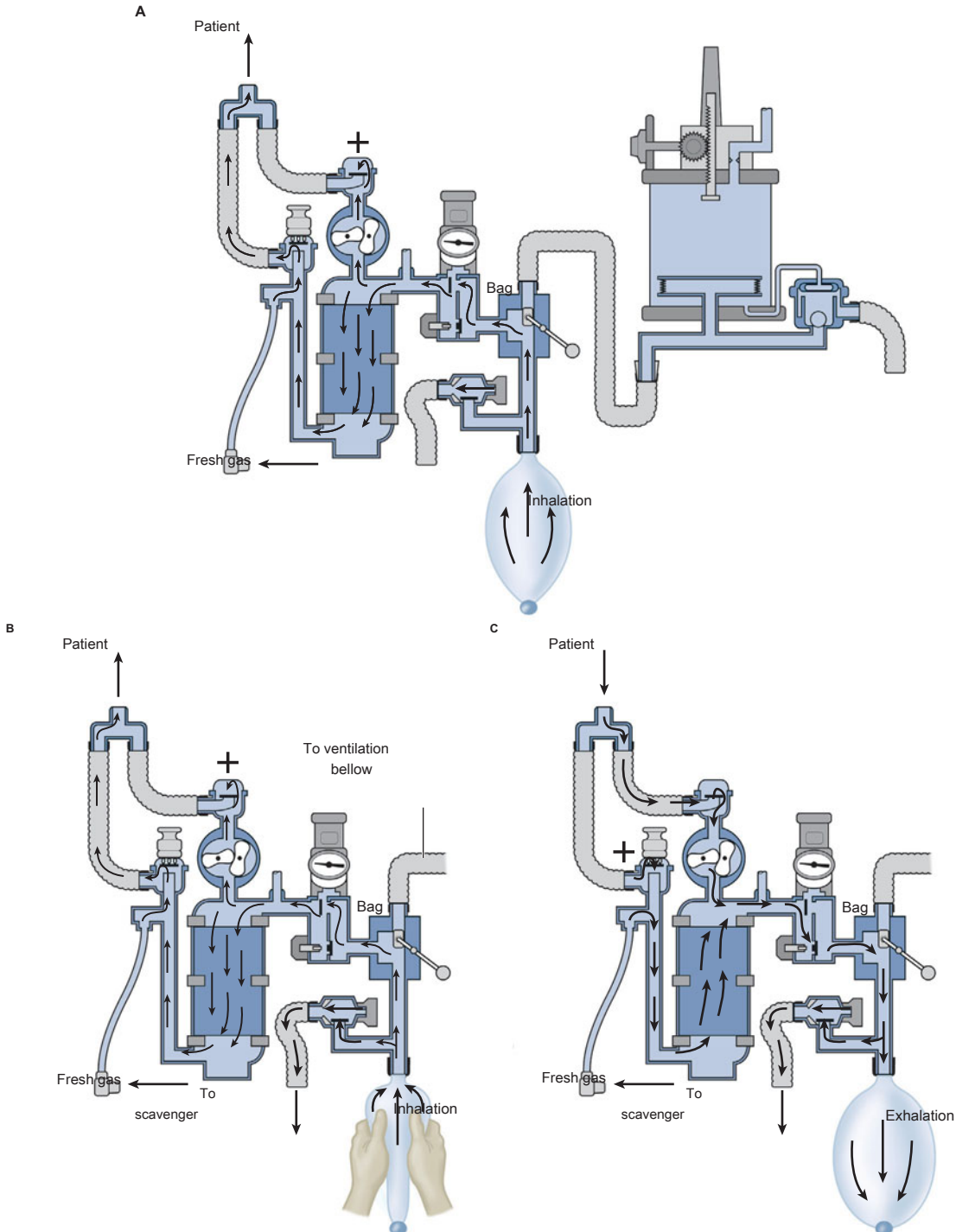

FIGURE 4•19 Diagram of a typical breathing circuit (Dräger Narkomed). Note gas fl ow during (**A**) spontaneous inspiration, (**B**) manual inspiration ("bagging"), and (**C**) exhalation (spontaneous or bag ventilation).

In most machines the common gas outlet is attached to the breathing circuit just past the exhala- tion valve to prevent artifi cially high exhaled tidal volume measurements. When spirometry measure- ments are made at the Y-connector, fresh gas fl ow can enter the circuit on the patient side of the inspiratory valve. Th e latter enhances CO_2 elimination and may help reduce desiccation of the CO_2 absorbent.

Newer anesthesia machines have integrated internalized breathing circuit components (Figure 4–20). Th e advantages of these designs include reduced probability of breathing circuit mis- connects, disconnects, kinks, and leaks. Th e smaller volume of compact machines can also help conserve gas fl ow and volatile anesthetics and allow faster changes in breathing circuit gas concentration. Internal heating of manifolds can reduce precipita- tion of moisture.

Oxygen Analyzers

General anesthesia should not be administered with- out an oxygen analyzer in the breathing circuit. **Th ree types of oxygen analyzers are available: polaro- graphic (Clark electrode), galvanic (fuel cell), and paramagnetic.** Th e fi rst two techniques utilize elec- trochemical sensors that contain cathode and anode electrodes embedded in an electrolyte gel separated from the sample gas by an oxygen-permeable mem- brane (usually Tefl on). As oxygen reacts with the electrodes, a current is generated that is proportional

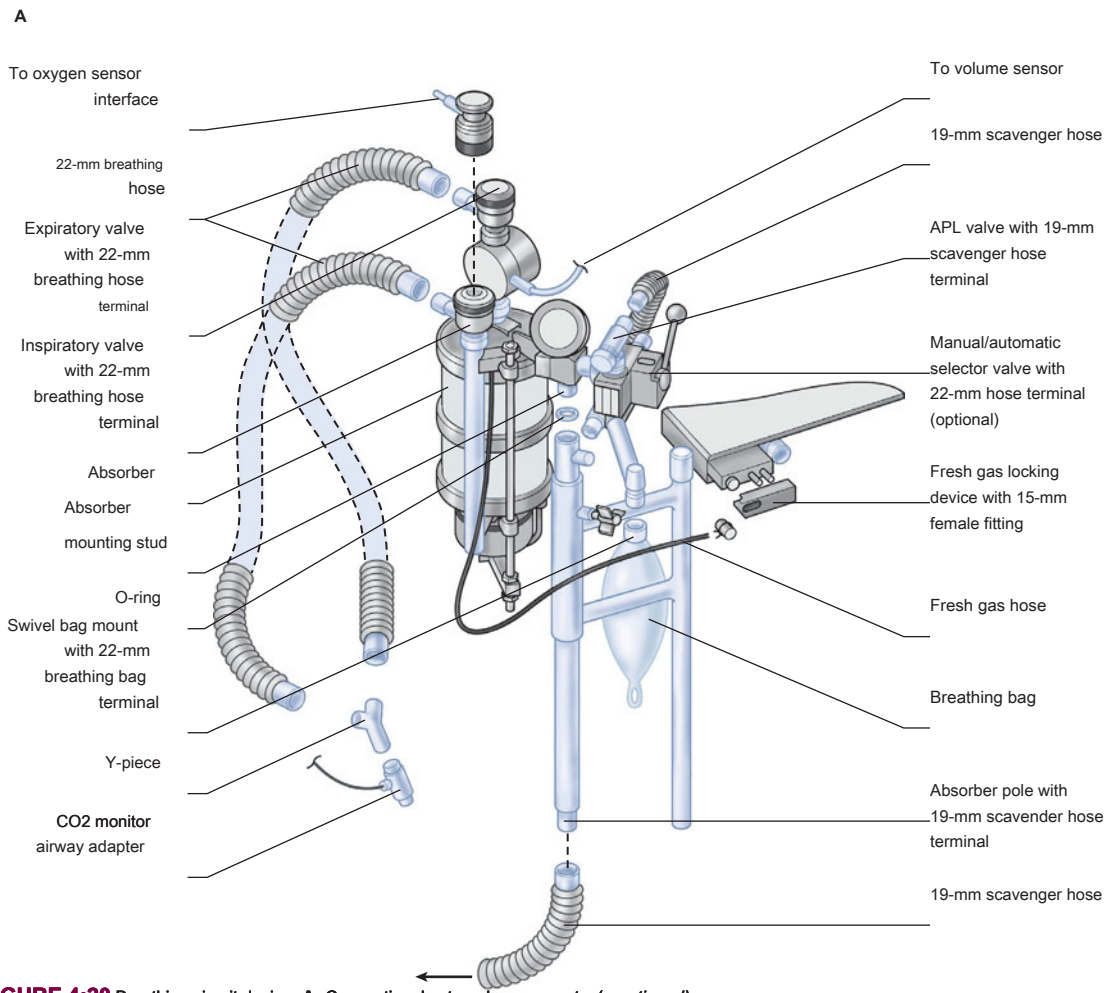

FIGURE 4•20 Breathing circuit design. **A:** Conventional external components. (*continued)*

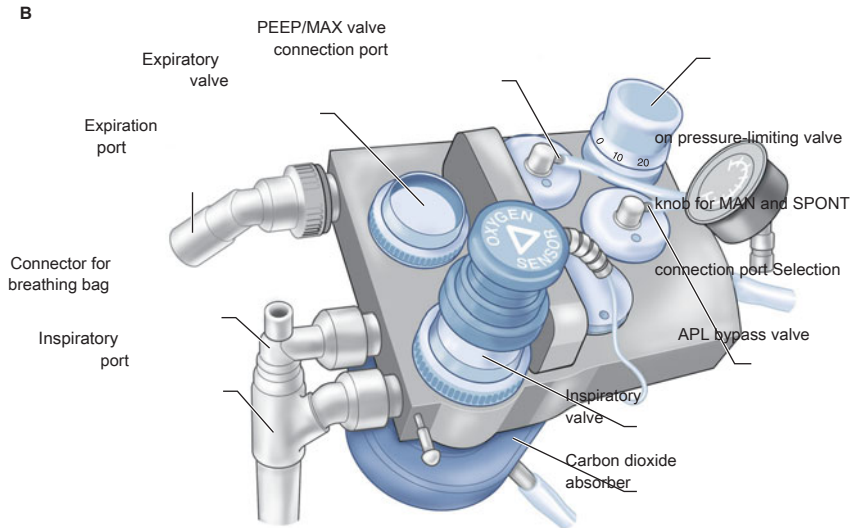

FIGURE 4•20 (*continued)* **B: Compact design that reduces external connections and circuit volume (Dräger Fabius GS).**

to the oxygen partial pressure in the sample gas. Th e galvanic and polarographic sensors diff er in the com- position of their electrodes and electrolyte gels. Th e components of the galvanic cell are capable of pro- viding enough chemical energy so that the reaction does not require an external power source.

Although the initial cost of paramagnetic sen- sors is greater than that of electrochemical sensors, paramagnetic devices are self-calibrating and have no consumable parts. In addition, their response time is fast enough to diff erentiate between inspired and expired oxygen concentrations.

All oxygen analyzers should have a low-level alarm that is automatically activated by turning on the anesthesia machine. Th e sensor should be placed into the inspiratory or expiratory limb of the circle system's breathing circuit—but *not* into the fresh gas line. As a result of the patient's oxygen consumption, the expiratory limb has a slightly lower oxygen par- tial pressure than the inspiratory limb, particularly at low fresh gas fl ows. Th e increased humidity of expired gas does not signifi cantly aff ect most mod- ern sensors.

Spirometers

Spirometers, also called respirometers, are used to measure exhaled tidal volume in the breathing cir- cuit on all anesthesia machines, typically near the exhalation valve. Some anesthesia machines also measure the inspiratory tidal volume just past the inspiratory valve or the actual delivered and exhaled tidal volumes at the Y-connector that attaches to the patient's airway.

A common method employs a rotating vane of low mass in the expiratory limb in front of the expi- ratory valve of the circle system (vane anemometer or Wright respirometer, **Figure 4–21A**).

Th e fl ow of gas across vanes within the respi- rometer causes their rotation, which is measured electronically, photoelectrically, or mechanically. In another variation using this turbine principle, the volumeter or displacement meter is designed to measure the movement of discrete quantities of gas over time (**Figure 4–21B**).

Changes in exhaled tidal volumes usually rep- resent changes in ventilator settings, but can also be due to circuit leaks, disconnections, or ventilator malfunction. Th ese spirometers are prone to errors caused by inertia, friction, and water condensa- tion. For example, Wright respirometers under- read at low fl ow rates and over-read at high fl ow rates. Furthermore, the measurement of exhaled tidal volumes at this location in the expiratory limb includes gas that had been lost to the circuit (and not delivered to the patient; discussed below). Th e diff erence between the volume of gas delivered to the circuit and the volume of gas actually reach- ing the patient becomes very signifi cant with long

compliant breathing tubes, rapid respiratory rates, and high airway pressures. Th ese problems are at least partially overcome by measuring the tidal vol- ume at the Y-connector to the patient's airway.

A hot-wire anemometer utilizes a fi ne platinum wire, electrically heated at a constant temperature, inside the gas fl ow. Th e cooling eff ect of increasing gas fl ow on the wire electrode causes a change in electrical resistance. In a constant-resistance ane- ometer, gas fl ow is determined from the current needed to maintain a constant wire temperature (and resistance). Disadvantages include an inability to detect reverse fl ow, less accuracy at higher fl ow rates, and the possibility that the heated wire may be a potential ignition source for fi re in the breathing manifold.

Ultrasonic fl ow sensors rely on discontinui- ties in gas fl ow generated by turbulent eddies in the fl ow stream. Upstream and downstream ultra- sonic beams, generated from piezoelectric crystals, are transmitted at an angle to the gas stream. Th e Doppler frequency shift in the beams is proportional to the fl ow velocities in the breathing circuit. Major advantages include the absence of moving parts and greater accuracy due to the device's independence from gas density.

Machines with variable-orifi ce fl owmeters usu- ally employ **two sensors (Figure 4–21C). One mea- sures fl ow at the** inspiratory port of the breathing system and the other measures fl ow at the expiratory port. Th ese sensors use a change in internal diam- eter to generate a pressure drop that is proportional to the fl ow through the sensor. Clear tubes con- nect the sensors to diff erential pressure transduc- ers inside the anesthesia machine (Datex-Ohmeda 7900 SmartVent). Th e changes in gas fl ows during the inspiratory and expiratory phases help the ven- tilator to adjust and provide a constant tidal volume. However, due to excessive condensation sensors can fail when used with heated humidifi ed circuits.

A pneumotachograph is a fi xed-orifi ce fl ow- meter that can function as a spirometer. A parallel bundle of small-diameter tubes in chamber (Fleisch pneumotachograph) or mesh screen provides a slight resistance to airfl ow. Th e pressure drop across this resistance is sensed by a diff erential pressure trans- ducer and is proportional to the fl ow rate. Integration of fl ow rate over time yields tidal volume. Moreover, analysis of pressure, volume, and time relationships can yield potentially valuable information about air- way and lung mechanics. Modifi cations have been required to overcome inaccuracies due to water con- densation and temperature changes. One modifi cation employs two pressure-sensing lines in a Pitot tube at the **Y-connection (Figure 4–21D). Gas fl ow- ing through the Pitot** tube (fl ow sensor tube) creates a pressure diff erence between the fl ow sensor lines. Th is pressure diff erential is used to measure fl ow, fl ow direction, and airway pressure. Respiratory gases are continuously sampled to correct the fl ow reading for changes in density and viscosity.

Circuit Pressure

A pressure gauge or electronic sensor is always used to measure breathing-circuit pressure somewhere between the expiratory and inspiratory unidirec- tional valves; the exact location depends on the model of anesthesia machine. Breathing-circuit pressure usually refl ects airway pressure if it is measured as close to the patient's airway as possible. Th e most accurate measurements of both inspira- tory and expiratory pressures can be obtained from the Y-connection (eg, D-lite and Pedi-lite sensors).

A rise in airway pressure may signal worsen- ing pulmonary compliance, an increase in tidal volume, or an obstruction in the breathing cir- cuit, tracheal tube, or the patient's airway. A drop in pressure may indicate an improvement in compli- ance, a decrease in tidal volume, or a leak in the cir- cuit. If circuit pressure is being measured at the CO_2 absorber, however, it will not always mirror the pressure in the patient's airway. For example, clamp- ing the expiratory limb of the breathing tubes dur- ing exhalation will prevent the patient's breath from exiting the lungs. Despite this buildup in airway pressure, a pressure gauge at the absorber will read zero because of the intervening one-way valve.

Some machines have incorporated auditory feedback for pressure changes during ventilator use.

Adjustable Pressure-Limiting Valve

Th e adjustable pressure-limiting (APL) valve, some- times referred to as the pressure relief or pop-off valve, is usually fully open during spontaneous

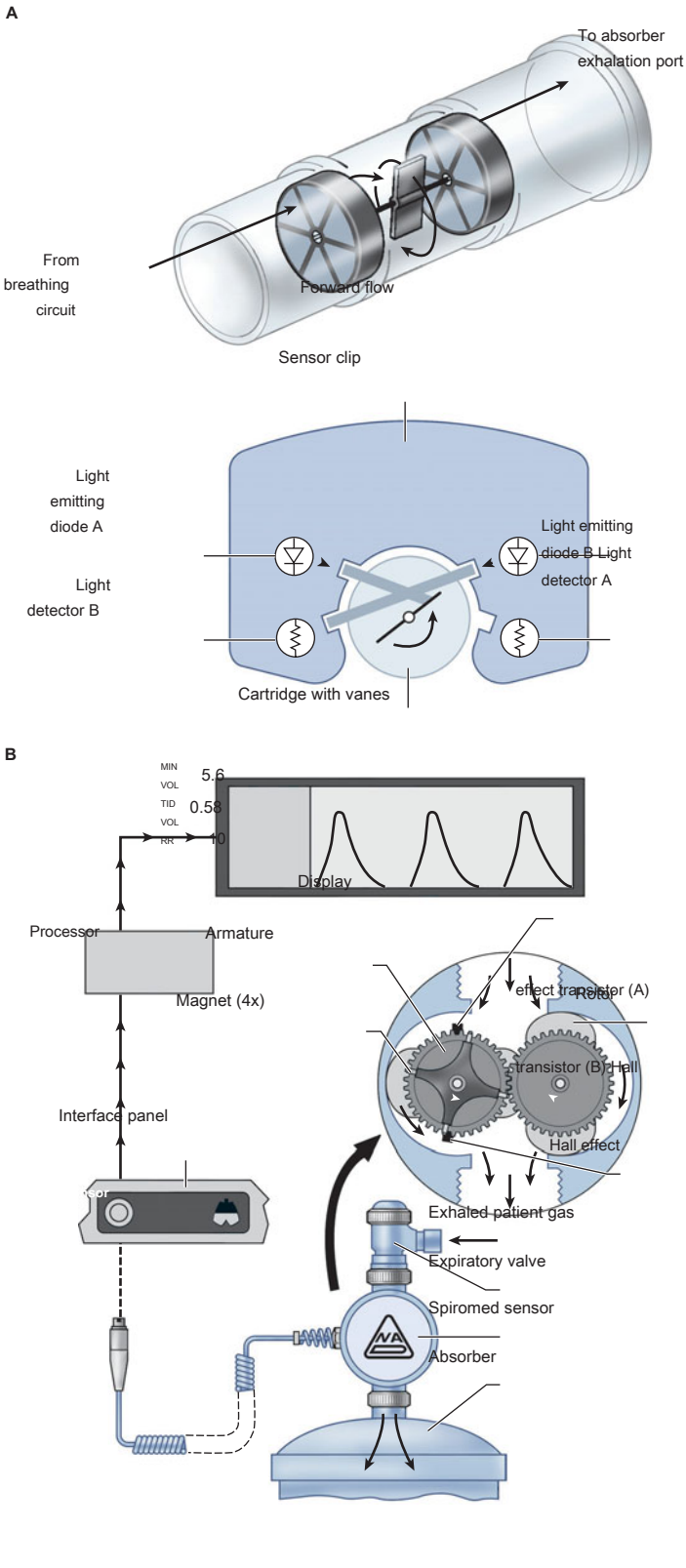

FIGURE 4•21 Spirometer designs.
A: Vane anemometer (Datex-Ohmeda).
B: Volumeter (Dräger).

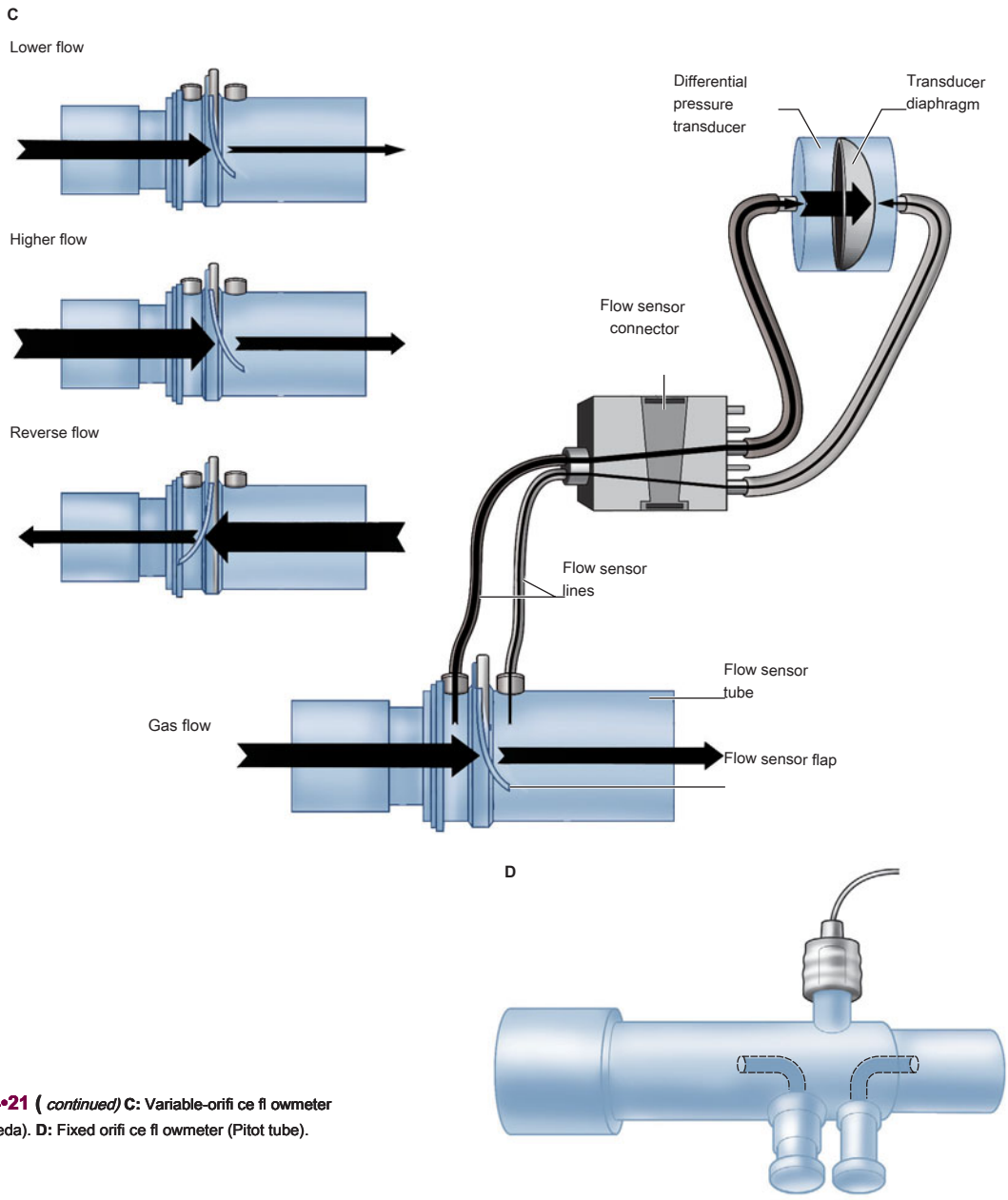

FIGURE 4•21 (*continued)* **C:** Variable-orifi ce fl owmeter (Datex-Ohmeda). **D:** Fixed orifi ce fl owmeter (Pitot tube).

ventilation but must be partially closed during manual or assisted bag ventilation. Th e APL valve oft en requires fi ne adjustments. If it is not closed suf- fi ciently excessive loss of circuit volume due to leaks prevents manual ventilation. At the same time if it is closed too much or is fully closed a progressive rise in pressure could result in pulmonary barotrauma (eg, pneumothorax) or hemodynamic compromise, or both. As an added safety feature, the APL valves on modern machines act as true pressure-limiting devices that can never be completely closed; the upper limit is usually 70–80 cm H_2O.

Humidifi ers

Absolute humidity is defi ned as the weight of water vapor in 1 L of gas (ie, mg/L). Relative humid- ity is the ratio of the actual mass of water present in a volume of gas to the maximum amount of water possible at a particular temperature. At 37°C and 100% relative humidity, absolute humidity is 44 mg/L, whereas at room temperature (21°C and 100% humidity) it is 18 mg/L. Inhaled gases in the operating room are normally administered at room temperature with little or no humidifi cation. Gases must therefore be warmed to body temperature and saturated with water by the upper respiratory tract. Tracheal intubation and high fresh gas fl ows bypass this normal humidifi cation system and expose the lower airways to dry (<10 mg H_2O/L), room tem- perature gases.

Prolonged humidifi cation of gases by the lower respiratory tract leads to dehydration of mucosa, altered ciliary function, and, if excessively pro- longed, could potentially lead to inspissation of secretions, atelectasis, and even ventilation/per- fusion mismatching, particularly in patients with underlying lung disease. Body heat is also lost as gases are warmed and even more importantly as water is vaporized to humidify the dry gases. Th e heat of vaporization for water is 560 cal/g of water vaporized. Fortunately, this heat loss accounts for about only 5–10% of total intraoperative heat loss, is not signifi cant for a short procedure (<1 h), and usually can easily be compensated for with a forced- air warming blanket. Humidifi cation and heating of inspiratory gases may be most important for small pediatric patients and older patients with severe underlying lung pathology, eg, cystic fi brosis.

A. Passive Humidifi ers

Humidifi ers added to the breathing circuit mini- mize water and heat loss. Th e simplest designs are condenser humidifi ers or heat and moisture exchanger (HME) units (Figure 4–22). Th ese pas- sive devices do not add heat or vapor but rather contain a hygroscopic material that traps exhaled humidifi cation and heat, which is released upon subsequent inhalation. Depending on the design, they may substantially increase apparatus dead space (more than 60 mL [3]), which can cause sig- nifi cant rebreathing in pediatric patients. Th ey can also increase breathing-circuit resistance and the work of breathing during spontaneous respira- tions. Excessive saturation of an HME with water or secretions can obstruct the breathing circuit. Some condenser humidifi ers also act as effective fi lters that may protect the breathing circuit and anesthesia machine from bacterial or viral cross-contamination. Th is may be particularly important when ventilating patients with respiratory infec- tions or compromised immune systems.

B. Active Humidifi ers

Active humidifi ers are more effective than passive ones in preserving moisture and heat. Active humid- ifi ers add water to gas by passing the gas over a water chamber (passover humidifi er) or through a satu- rated wick (wick humidifi er), bubbling it through water (bubble-through humidifi er), or mixing it with vaporized water (vapor-phase humidifi er). Because increasing temperature increases the capacity of a gas to hold water vapor, heated humidifi ers with ther- mostatically controlled elements are most effective.

Th e hazards of heated humidifi ers include ther- mal lung injury (inhaled gas temperature should be monitored and should not exceed 41°C), noso- comial infection, increased airway resistance from excess water condensation in the breathing cir- cuit, interference with fl owmeter function, and an increased likelihood of circuit disconnection. Th ese humidifi ers are particularly valuable with children as they help prevent both hypothermia and the plug- ging of small tracheal tubes by dried secretions. Of course, any design that increases airway dead space should be avoided in pediatric patients. Unlike pas- sive humidifi ers, active humidifi ers do not fi lter respiratory gases.

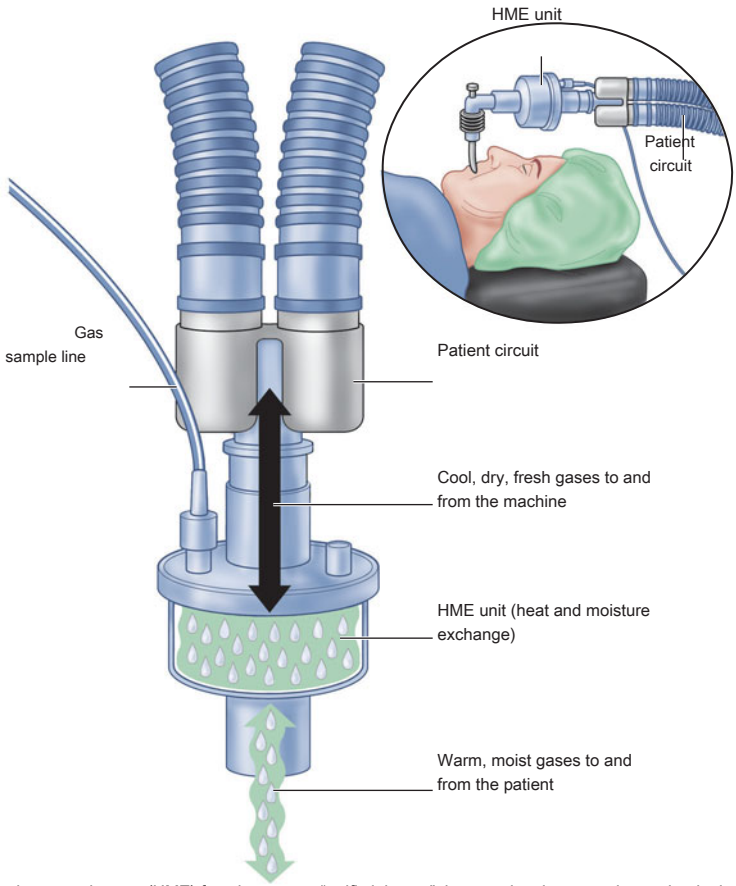

FIGURE 4•22 Heat and moisture exchanger (HME) functions as an "artifi cial nose" that attaches between the tracheal tube and the right-angle connector of the breathing circuit.

VENTILATORS

Ventilators are used extensively in the operating room (OR) and the intensive care unit (ICU). All modern anesthesia machines are equipped with a ventilator. Historically OR ventilators were simpler and more compact than their ICU counterparts. Th is distinction has become blurred due to advances in technology together with an increasing need for "ICU-type" ventilators as more critically ill patients come to the OR. Th e ventilators on some modern machines are just as sophisticated as those in the ICU and have almost the same capabilities. Aft er a general discussion of basic ventilator principles, this section reviews the use of ventilators in conjunction with anesthesia machines.

Overview

Ventilators generate gas fl ow by creating a pres- sure gradient between the proximal airway and the alveoli. Older units relied on the generation of nega- tive pressure around (and inside) the chest (eg, iron lungs), whereas modern ventilators generate positive pressure and gas fl ow in the upper airway.

Ventilator function is best described in rela- tion to the four phases of the ventilatory cycle: inspiration, the transition from inspiration to expiration, expiration, and the transition from expiration to inspiration. Although several clas- sifi cation schemes exist, the most common is based on inspiratory phase characteristics and the method of cycling from inspiration to expiration.

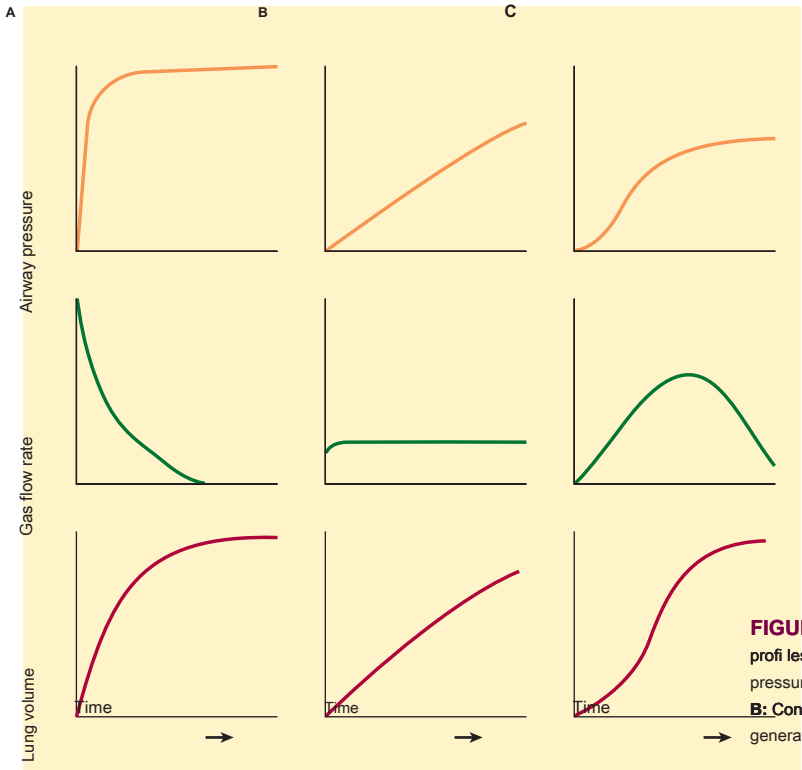

FIGURE 4•23 Pressure, volume, and fl ow profi les of diff erent types of ventilators. **A:** Constant pressure. **B:** Constant fl ow. **C:** Nonconstant generator.

Other classifi cation categories may include power source (eg, pneumatic-high pressure, pneumatic- Venturi, or electric), design (single-circuit system, double-circuit system, rotary piston, linear piston), and control mechanisms (eg, electronic timer or microprocessor).

A. Inspiratory Phase

During inspiration, ventilators generate tidal volumes by producing gas fl ow along a pressure gradient. Th e machine generates either a con- stant pressure (constant-pressure generators) or constant gas fl ow rate (constant-fl ow generators) during inspiration, regardless of changes in lung mechanics (Figure 4–23). Nonconstant generators produce pressures or gas fl ow rates that vary dur- ing the cycle but remain consistent from breath to breath. For instance, a ventilator that generates a fl ow pattern resembling a half cycle of a sine wave (eg, rotary piston ventilator) would be classifi ed as a nonconstant-fl ow generator. An increase in airway resistance or a decrease in lung compliance would increase peak inspiratory pressure but would not alter the fl ow rate generated by this type of ventila- tor (Figure 4–24).

B. Transition Phase from Inspiration to Expiration

Termination of the inspiratory phase can be trig- gered by a preset limit of time (fi xed duration), a set inspiratory pressure that must be reached, or a predetermined tidal volume that must be deliv- ered. Time-cycled ventilators allow tidal volume and peak inspiratory pressure to vary depend- ing on lung compliance. Tidal volume is adjusted by setting inspiratory duration and inspiratory fl ow rate.

Pressure-cycled ventilators will not cycle from the inspiratory phase to the expiratory phase until a preset pressure is reached. If a large circuit leak decreases peak pressures signifi cantly,

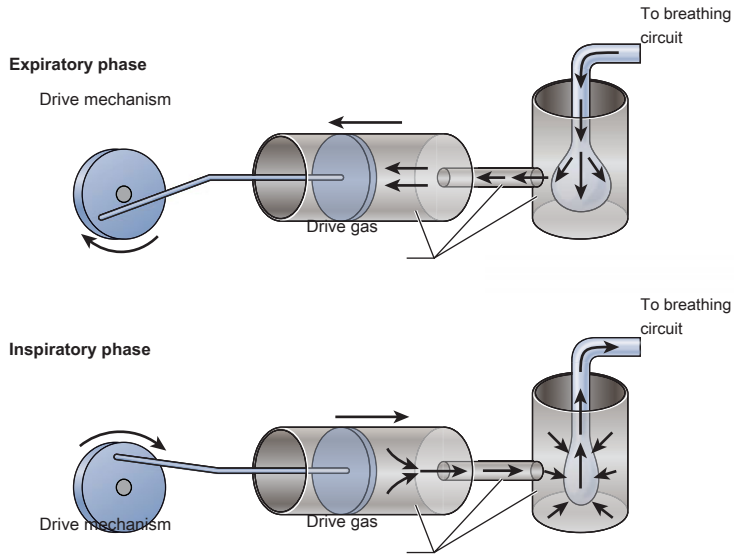

FIGURE 4•24 Rotary piston ventilator.

a pressure-cycled ventilator may remain in the inspiratory phase indefi nitely. On the other hand, a small leak may not markedly decrease tidal vol- ume, because cycling will be delayed until the pressure limit is met. Volume-cycled ventilators vary inspiratory duration and pressure to deliver a preset volume. In reality, modern ventilators over- come the many shortcomings of classic ventilator designs by incorporating secondary cycling param- eters or other limiting mechanisms. For example, time-cycled and volume-cycled ventilators usu- ally incorporate a pressure-limiting feature that terminates inspiration when a preset, adjustable safety pressure limit is reached. Similarly a volume- preset control that limits the excursion of the bel- lows allows a time-cycled ventilator to function somewhat like a volume-cycled ventilator, depend- ing on the selected ventilator rate and inspiratory fl ow rate.

C. Expiratory Phase

Th e expiratory phase of ventilators normally reduces airway pressure to atmospheric levels or some preset value of positive end-expiratory pressure (PEEP). Exhalation is therefore passive. Flow out of the lungs is determined primarily by airway resistance and lung compliance. Expired gases fi ll up the bellows; they are then relieved to the scavenging system. PEEP is usually created with an adjustable spring valve mechanism or pneumatic pressurization of the exhalation (spill) valve.

D. Transition Phase from Expiration to Inspiration

Transition into the next inspiratory phase may be based on a preset time interval or a change in pressure. Th e behavior of the ventilator during this phase together with the type of cycling from inspi- ration to expiration determines ventilator mode.

During controlled ventilation, the most basic mode of all ventilators, the next breath always occurs aft er a preset time interval. Th us tidal vol- ume and rate are fi xed in volume-controlled ven- tilation, whereas peak inspiratory pressure is fi xed in pressure-controlled ventilation. Controlled ventilation modes are not designed for spontane- ous breathing. In the volume-control mode, the ventilator adjusts gas fl ow rate and inspiratory time based on the set ventilatory rate and I:E ratio (Figure 4–25 A). In the pressure-control mode, inspiratory time is also based on the set ventilator rate and inspiratory-to-expiratory (I:E) ratio, but gas fl ow is adjusted to maintain a constant inspira- tory pressure (Figure 4–25B).

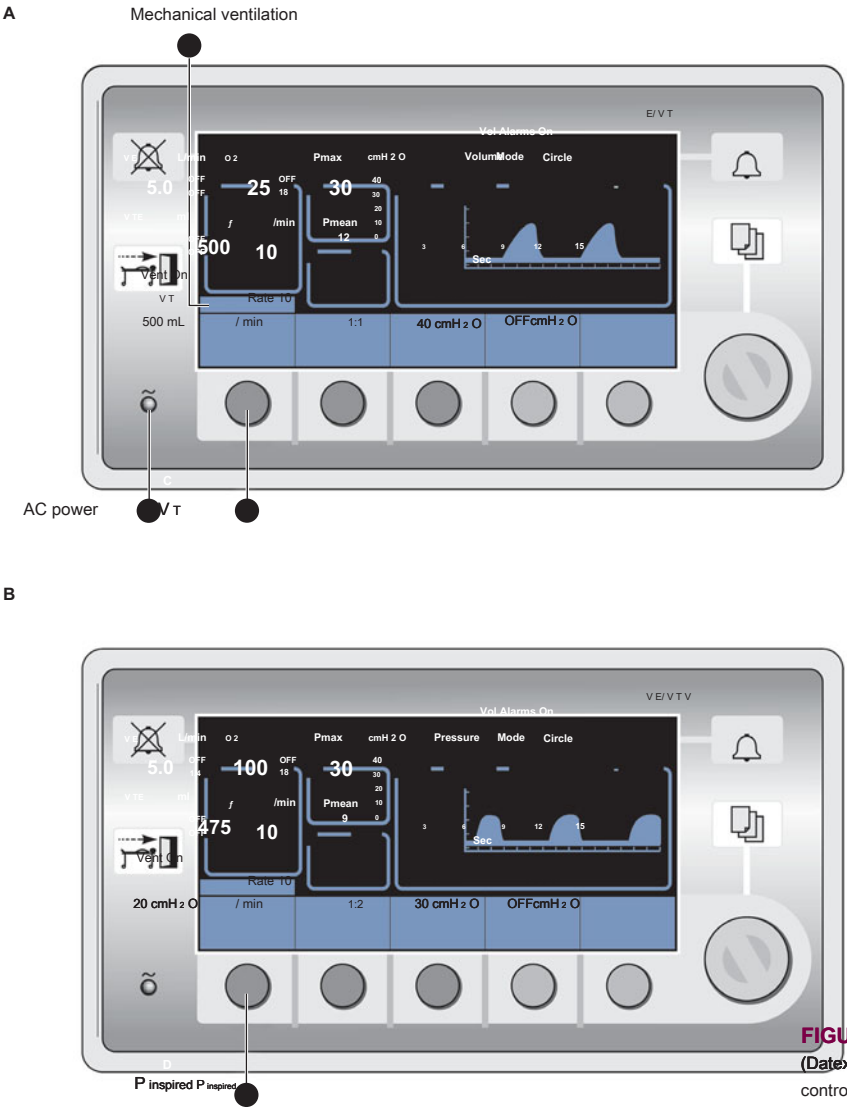

FIGURE 4•25 Ventilator controls (Datex-Ohmeda). **A:** Volume control mode. **B:** Pressure control mode.

In contrast, intermittent mandatory ventila- tion (IMV) allows patients to breathe spontaneously between controlled breaths. Synchronized inter- mittent mandatory ventilation (SIMV) is a further refi nement that helps prevent “fi ghting the ventila- tor” and “breath stacking”; whenever possible, the ventilator tries to time the mandatory mechanical breaths with the drops in airway pressure below the end-expiratory pressure that occur as the patient ini- tiates a spontaneous breath.

Ventilator Circuit Design

Traditionally ventilators on anesthesia ma chines have a double-circuit system design and are pneumatically powered and electronically controlled (Figure 4–26). Newer machines also incorporate microprocessor control that relies on sophisticated pressure and fl ow sensors. Th is feature allows multiple ventilatory modes, electronic PEEP, tidal volume modulation, and enhanced safety

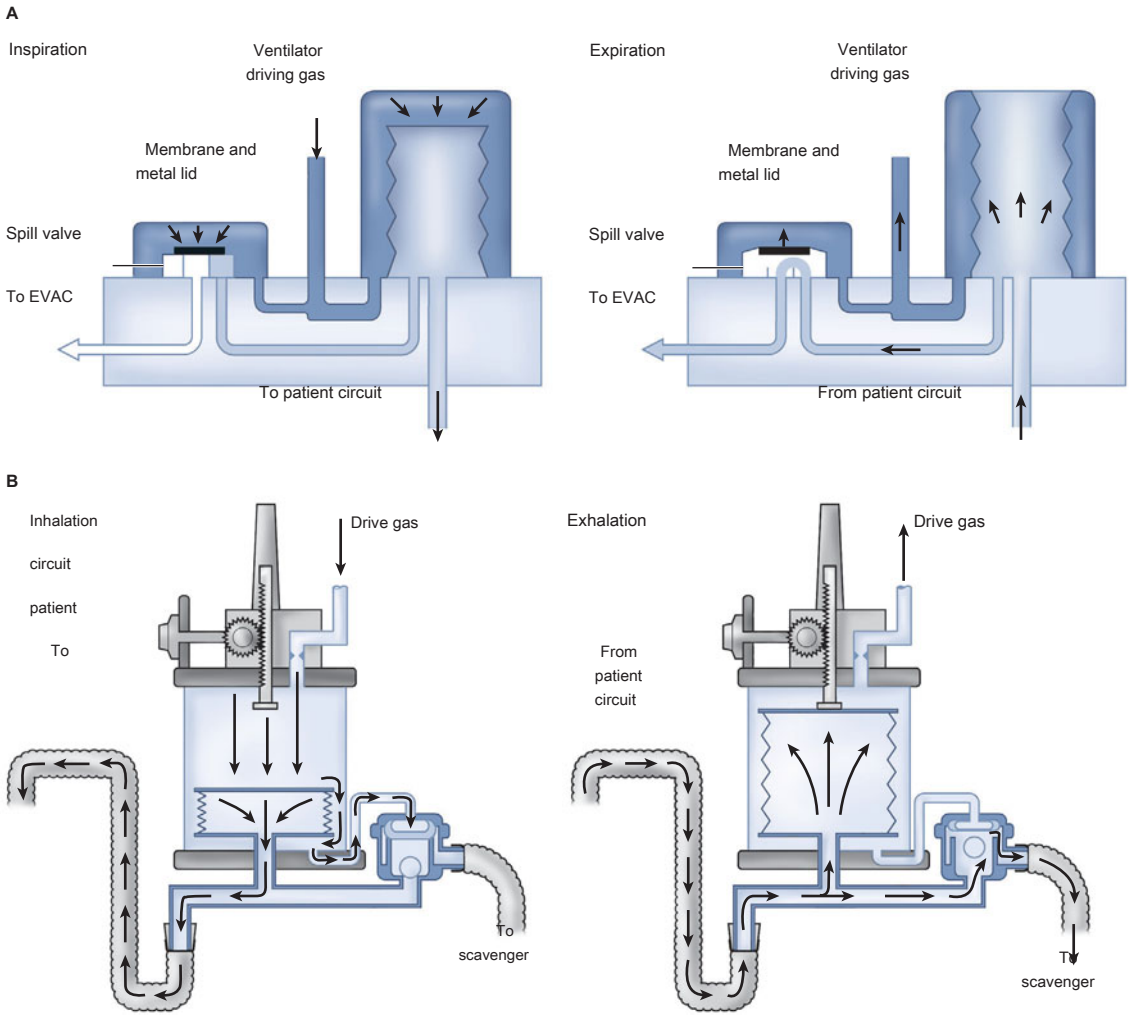

FIGURE 4•26 Double-circuit pneumatic ventilator design. **A:** Datex-Ohmeda. **B:** Dräger.

features. Some anesthesia machines have ventilators that use a single-circuit piston design (Figure 4–24).

A. Double-Circuit System Ventilators

In a double-circuit system design, tidal volume is delivered from a bellows assembly that con- sists of a bellows in a clear rigid plastic enclosure (Figure 4–26). A standing (ascending) bellows is preferred as it readily draws attention to a circuit disconnection by collapsing. Hanging (descending) bellows are rarely used and must not be weighted; older ventilators with weighted hanging bellows continue to fi ll by gravity despite a disconnection in the breathing circuit.

Th e bellows in a double-circuit design ventila- tor takes the place of the breathing bag in the anes- thesia circuit. Pressurized oxygen or air from the ventilator power outlet (45–50 psig) is routed to the space between the inside wall of the plastic enclosure and the outside wall of the bellows. Pressurization of the plastic enclosure compresses the pleated bel- lows inside, forcing the gas inside into the breathing

circuit and patient. In contrast, during exhalation, the bellows ascend as pressure inside the plastic enclosure drops and the bellows fi ll up with the exhaled gas. A ventilator fl ow control valve regu- lates drive gas fl ow into the pressurizing chamber. Th is valve is controlled by ventilator settings in the control box (Figure 4–26). Ventilators with micro- processors also utilize feedback from fl ow and pres- sure sensors. If oxygen is used for pneumatic power it will be consumed at a rate at least equal to minute ventilation. Th us, if oxygen fresh gas fl ow is 2 L/min and a ventilator is delivering 6 L/min to the circuit, a total of at least 8 L/min of oxygen is being con- sumed. Th is should be kept in mind if the hospi- tal's medical gas system fails and cylinder oxygen is required. Some anesthesia machines reduce oxygen consumption by incorporating a Venturi device that draws in room air to provide air/ oxygen pneumatic power. Newer machines may off er the option of using compressed air for pneumatic power. A leak in the ventilator bellows can transmit high gas pres- sure to the patient's airway, potentially resulting in pulmonary barotrauma. **Th is may be indicated by a higher than expected rise in inspired oxygen con- centration (if oxygen is the sole pressurizing gas).**

Some machine ventilators have a built-in drive gas regulator that reduces the drive pressure (eg, to 25 psig) for added safety.

Double-circuit design ventilators also incor- porate a free breathing valve that allows outside air to enter the rigid drive chamber and the bellows to collapse if the patient generates negative pressure by taking spontaneous breaths during mechanical ventilation.

B. Piston Ventilators

In a piston design, the ventilator substitutes an elec- trically driven piston for the bellows (Figure 4–24); the ventilator requires either minimal or no pneu-

matic (oxygen) power. Th e major advantage of a piston ventilator is its ability to deliver accu- rate tidal volumes to patients with very poor lung compliance and to very small patients. During volume-controlled ventilation the piston moves at a constant velocity whereas during pressure- controlled ventilation the piston moves with decreasing velocity. As with the bellows, the piston fi lls with gas from the breathing circuit. To prevent generation of signifi cant negative pressure during the downstroke of the piston the circle system confi gura- tion has to be modifi ed (Figure 4–27). Th e ventilator must also incorporate a negative-pressure relief valve or be capable of terminating the piston's downstroke if negative pressure is detected. Introduction of a negative-pressure relief valve to the breathing circuit may introduce the risk of air entrainment and the potential for dilution of oxygen and volatile anes- thetic concentrations if the patient breathes during mechanical ventilation and low fresh gas fl ows.

C. Spill Valve

Whenever a ventilator is used on an anesthesia machine, the circle system's APL valve must be functionally removed or isolated from the circuit. A bag/ventilator switch typically accomplishes this. When the switch is turned to "bag" the ventilator is excluded and spontaneous/manual (bag) ventila- tion is possible. When it is turned to "ventilator," the breathing bag and the APL are excluded from the breathing circuit. Th e APL valve may be automati- cally excluded in some newer anesthesia machines when the ventilator is turned on. Th e ventilator con- tains its own pressure-relief (pop-off) valve, called the spill valve, which is pneumatically closed during inspiration so that positive pressure can be gener- ated (Figure 4–26). During exhalation, the pressur- izing gas is vented out and the ventilator spill valve is no longer closed. Th e ventilator bellows or piston refi ll during expiration; when the bellows is com- pletely fi lled, the increase in circle system pressure causes the excess gas to be directed to the scavenging system through the spill valve. Sticking of this valve can result in abnormally elevated airway pressure during exhalation.

Pressure & Volume Monitoring

Peak inspiratory pressure is the highest circuit pressure generated during an inspiratory cycle, and provides an indication of dynamic compli- ance. Plateau pressure is the pressure measured during an inspiratory pause (a time of no gas fl ow), and mirrors static compliance. During

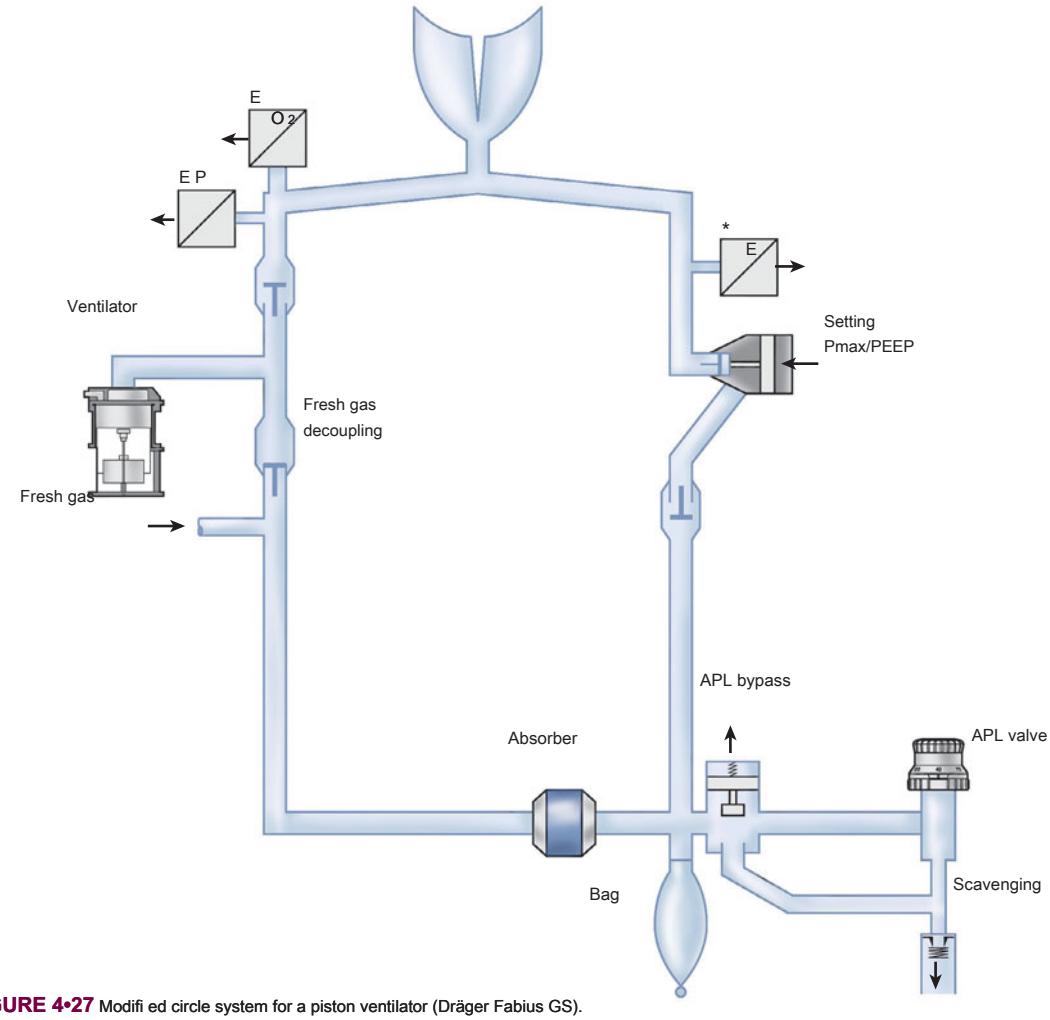

FIGURE 4•27 Modifi ed circle system for a piston ventilator (Dräger Fabius GS).

normal ventilation of a patient without lung dis- ease, peak inspiratory pressure is equal to or only slightly greater than plateau pressure. An increase in both peak inspiratory pressure and plateau pressure implies an increase in tidal volume or a decrease in pulmonary compliance. An increase in peak inspira- tory pressure without any change in plateau pressure signals an increase in airway resistance or inspira- tory gas fl ow rate (Table 4–3). Th us, the shape of the breathing-circuit pressure waveform can provide important airway information. Many anesthesia machines graphically display breathing-circuit pres- sure (Figure 4–28). Airway secretions or kinking of the tracheal tube can be easily ruled out with the use of a suction catheter. Flexible fi beroptic bronchos- copy will usually provide a defi nitive diagnosis.

Ventilator Alarms

Alarms are an integral part of all modern anesthe- sia ventilators. Whenever a ventilator is used “disconnect alarms” must be passively acti- vated. Anesthesia workstations should have at least

TABLE 4•3 Causes of increased peak inspiratory pressure (PIP), with or without an increased plateau pressure (PP).

Increased PIP and PP
Increased tidal volume
Decreased pulmonary compliance
Pulmonary edema Trendelenburg position Pleural effusion Ascites
Abdominal packing Peritoneal gas insufflation Tension pneumothorax Endobronchial intubation
Increased PIP and Unchanged PP
Increased inspiratory gas flow rate
Increased airway resistance
Kinked endotracheal tube
Bronchospasm Secretions
Foreign body aspiration
Airway compression
Endotracheal tube cuff herniation

three disconnect alarms: low peak inspiratory pres- sure, low exhaled tidal volume, and low exhaled car- bon dioxide. Th e fi rst is always built into the ventilator whereas the latter two may be in separate modules. A small leak or partial breathing-circuit disconnection may be detected by subtle decreases in peak inspiratory pressure, exhaled volume, or end-tidal carbon dioxide before alarm thresholds are reached. Other built-in ventilator alarms include high peak inspiratory pressure, high PEEP, sustained high airway pressure, negative pressure, and low oxygen-supply pressure. Most modern anesthesia ventilators also have integrated spirometers and oxygen analyzers that provide additional alarms.

Problems Associated with Anesthesia Ventilators

A. Ventilator–Fresh Gas Flow Coupling

From the previous discussion, it is important to appreciate that because the ventilator's spill valve is closed during inspiration, fresh gas fl ow from the machine's common gas outlet normally contrib- utes to the tidal volume delivered to the patient. For example, if the fresh gas fl ow is 6 L/min, the I:E ratio is 1:2, and the respiratory rate is 10 breaths/min, each tidal volume will include an extra 200 mL in addition to the ventilator's output:

(6000 mL/min) (33%)
10 breaths/min ≈ 200 mL/breath

Th us, increasing fresh gas fl ow increases tidal volume, minute ventilation, and peak inspiratory pressure. To avoid problems with ventilator–fresh gas fl ow coupling, airway pressure and exhaled tidal volume must be monitored closely and excessive fresh gas fl ows must be avoided.

B. Excessive Positive Pressure

Intermittent or sustained high inspiratory pressures (>30 mm Hg) during positive-pressure ventilation increase the risk of pulmonary barotrauma (eg, pneumothorax) or hemodynamic compromise, or both, during anesthesia. Excessively high pressures may arise from incorrect settings on the ventilator, ventilator malfunction, fresh gas fl ow coupling (above), or activation of the oxygen fl ush during the inspiratory phase of the ventilator. Use of the oxygen fl ush valve during the inspiratory cycle of a ventilator *must be avoided* because the ventilator spill valve will be closed and the APL valve is excluded; the surge of oxygen (600–1200 mL/s) and circuit pressure will be transferred to the patient's lungs.

In addition to a high-pressure alarm, all venti- lators have a built-in automatic or APL valve. Th e mechanism of pressure limiting may be as simple as a threshold valve that opens at a certain pressure or electronic sensing that abruptly terminates the ven- tilator inspiratory phase.

C. Tidal Volume Discrepancies

Large discrepancies between the set and actual tidal volume that the patient receives are oft en observed in the operating room during volume con- trol ventilation. Causes include breathing-circuit compliance, gas compression, ventilator–fresh gas fl ow coupling (above), and leaks in the anesthe- sia machine, the breathing circuit, or the patient's airway.

Th e compliance for standard adult breath- ing circuits is about 5 mL/cm H_2O. Th us, if peak

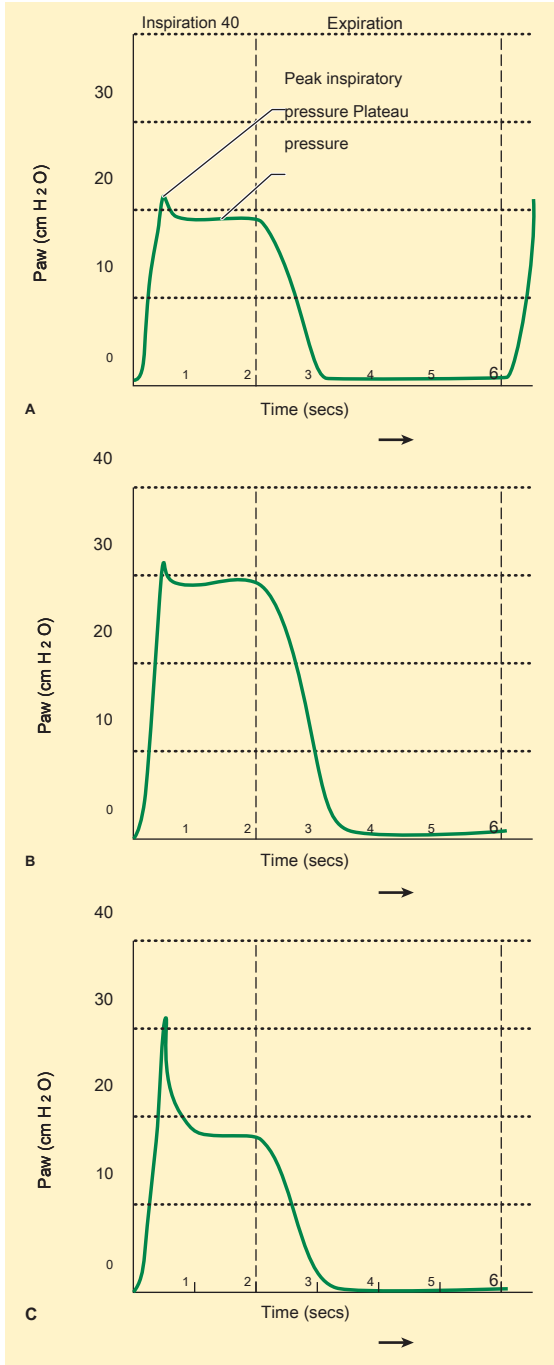

FIGURE 4•28 Airway pressures (Paw) can be diagrammatically presented as a function of time. **A:** In normal persons, the peak inspiratory pressure is equal to or slightly greater than the plateau pressure. **B:** An increase in peak inspiratory pressure and plateau pressure (the diff erence between the two remains almost constant) can be due to an increase in tidal volume or a decrease in pulmonary compliance. **C:** An increase in peak inspiratory pressure with little change in plateau pressure signals an increase in inspiratory fl ow rate or an increase in airway resistance.

inspiratory pressure is 20 cm H_2O, about 100 mL of set tidal volume is lost to expanding the circuit. For this reason breathing circuits for pediatric patients are designed to be much stiff er, with compliances as small as 1.5–2.5 mL/cm H_2O.

Compression losses, normally about 3%, are due to gas compression within the ventilator bellows and may be dependent on breathing-circuit volume. Th us if tidal volume is 500 mL another 15 mL of the set tidal gas may be lost. Gas sampling for capnog- raphy and anesthetic gas measurements represent additional losses in the form of gas leaks unless the sampled gas is returned to the breathing circuit, as occurs in some machines.

Accurate detection of tidal volume discrepan- cies is dependent on where the spirometer is placed. Sophisticated ventilators measure both inspira- tory and expiratory tidal volumes. It is important to note that unless the spirometer is placed at the Y-connector in the breathing circuit, compliance and compression losses will not be apparent.

Several mechanisms have been built into newer anesthesia machines to reduce tidal volume discrep- ancies. During the initial electronic self-checkout, some machines measure total system compliance and subsequently use this measurement to adjust the excursion of the ventilator bellows or piston; leaks may also be measured but are usually not compensated. Th e actual method of tidal volume compensation or modulation varies according to manufacturer and model. In one design a fl ow sensor measures the tidal volume delivered at the inspiratory valve for the fi rst few breaths and adjusts subsequent metered drive gas fl ow volumes to compensate for tidal volume losses (feedback adjustment). Another design continually measures fresh gas and vaporizer fl ow and subtracts this amount from the metered drive gas fl ow (pre- emptive adjustment). Alternately, machines that use electronic control of gas fl ow can decouple fresh gas fl ow from the tidal volume by delivery of fresh gas fl ow only during exhalation. Lastly, the inspiratory phase of the ventilator–fresh gas fl ow may be diverted through a decoupling valve into the breathing bag, which is excluded from the circle system during venti- lation. During exhalation the decoupling valve opens, allowing the fresh gas that was temporarily stored in the bag to enter the breathing circuit.

WASTE•GAS SCAVENGERS

Waste-gas scavengers dispose of gases that have been vented from the breathing cir- cuit by the APL valve and ventilator spill valve. Pollution of the operating room environment with anesthetic gases may pose a health hazard to sur- gical personnel. Although it is diffi cult to defi ne safe levels of exposure, the National Institute for Occupational Safety and Health (NIOSH) recom- mends limiting the room concentration of nitrous oxide to 25 ppm and halogenated agents to 2 ppm (0.5 ppm if nitrous oxide is also being used) in time-integrated samples. Reduction to these trace levels is possible only with properly functioning waste-gas scavenging systems.

To avoid the buildup of pressure, excess gas volume is vented through the APL valve in the breathing circuit and the ventilator spill valve. Both valves should be connected to hoses (transfer tub- ing) leading to the scavenging interface, which may be inside the machine or an external attachment (**Figure 4–29**). Th e pressure immediately down- stream to the interface should be kept between 0.5 and +3.5 cm H_2O during normal operating condi- tions. Th e scavenging interface may be described as either open or closed.

An open interface is open to the outside atmosphere and usually requires no pressure relief valves. In contrast, a closed interface is closed to the outside atmosphere and requires negative- and positive-pressure relief valves that protect the patient from the negative pressure of the vacuum system and positive pressure from an obstruction in the disposal tubing, respectively. Th e outlet of the scavenging system may be a direct line to the outside via a ventilation duct beyond any point of recirculation (passive scavenging) or a con- nection to the hospital's vacuum system (active scavenging). A chamber or reservoir bag accepts waste-gas overfl ow when the capacity of the vac- uum is exceeded. Th e vacuum control valve on an active system should be adjusted to allow the evacuation of 10–15 L of waste gas per minute. Th is rate is adequate for periods of high fresh gas fl ow (ie, induction and emergence) yet minimizes the risk of transmitting negative pressure to the breathing circuit during lower fl ow conditions

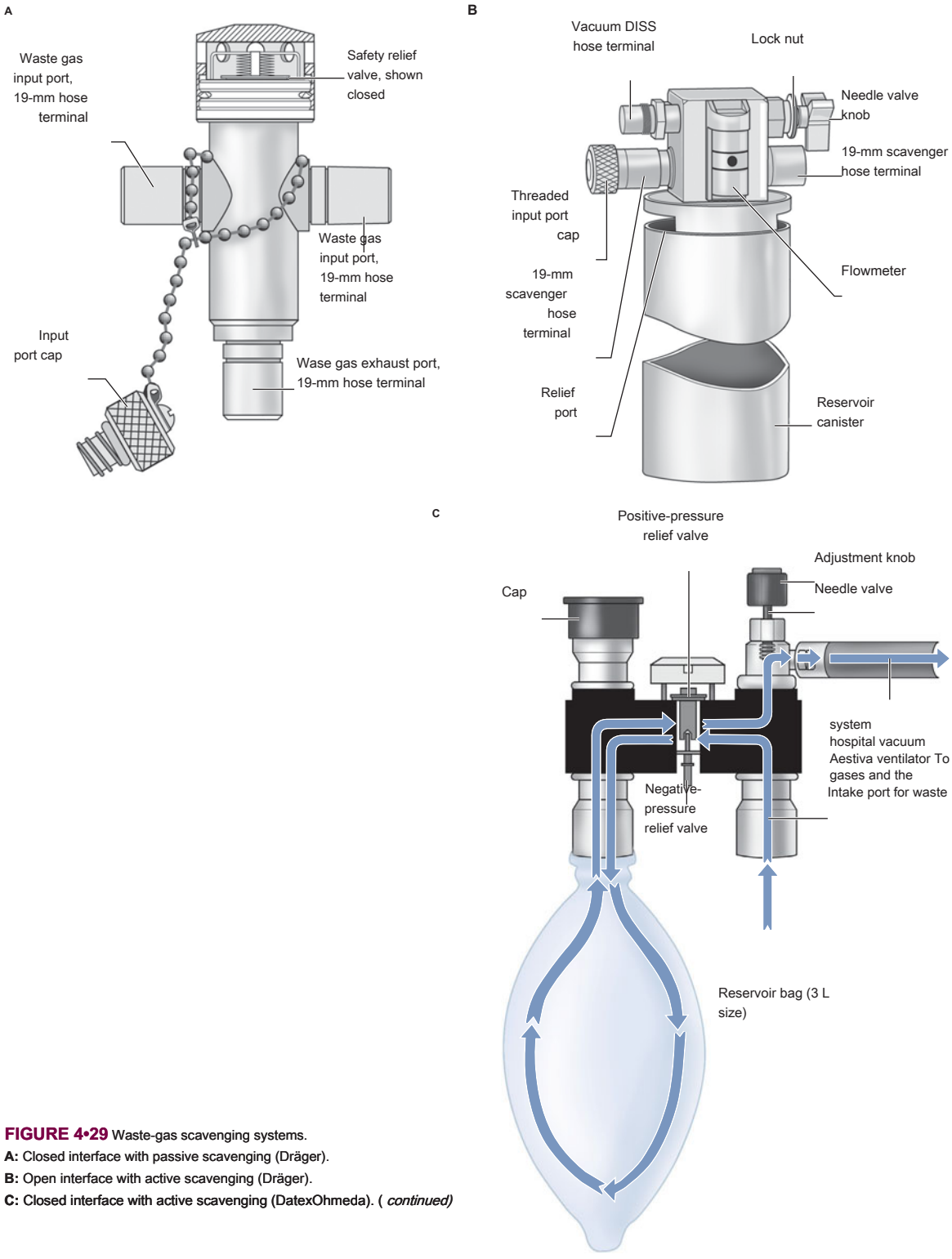

FIGURE 4•29 Waste-gas scavenging systems.
A: Closed interface with passive scavenging (Dräger).
B: Open interface with active scavenging (Dräger).
C: Closed interface with active scavenging (DatexOhmeda). (*continued)*

D

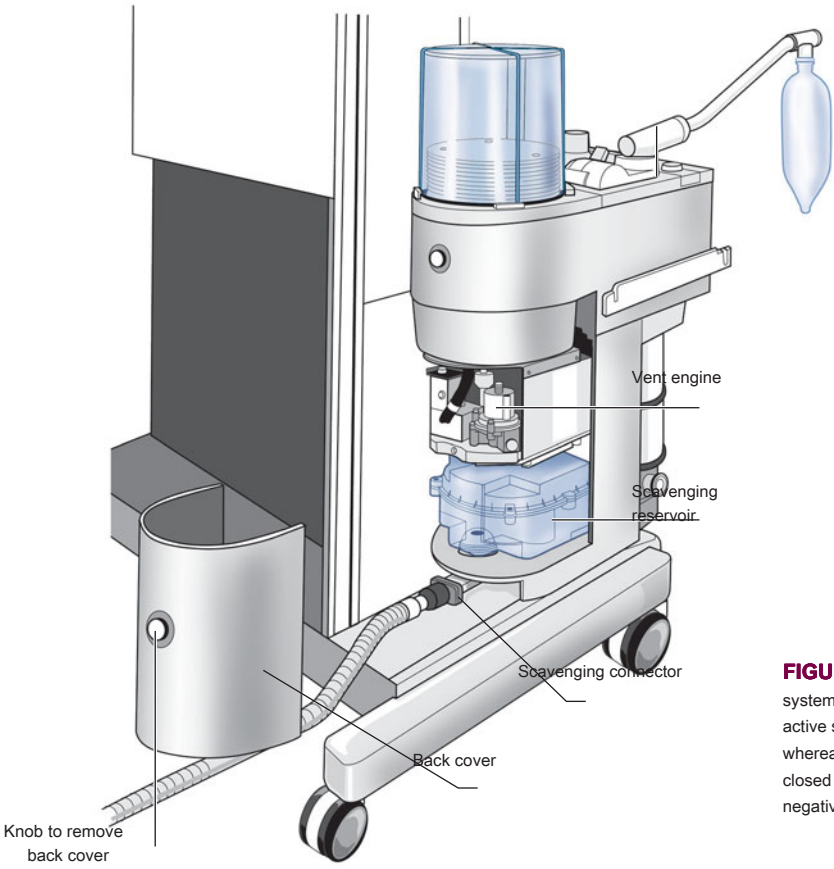

FIGURE 4•29 (*continued)* **D: Builtin scavenging** system that can be either active or passive; the active scavenging option has an open interface whereas the passive scavenging option has a closed interface with positive- and negative-pressure relief valves (Datex-Ohmeda).

(maintenance). Unless used correctly the risk of occupational exposure for health care providers is higher with an open interface. Some machines may come with both active and passive scavenger systems.

ANESTHESIA MACHINE CHECKOUT LIST

Misuse or malfunction of anesthesia gas delivery equipment can cause major morbidity or mortality.

A routine inspection of anesthesia equipment before each use increases operator familiarity and confi rms proper functioning. Th e U.S. Food and Drug Administration (FDA) has made available a generic checkout procedure for anesthesia gas machines and breathing systems (Table 4–4). Th is procedure should be modifi ed as necessary, depend- ing on the specifi c equipment being used and the manufacturer's recommendations. Note that although the entire checkout does not need to be repeated between cases on the same day, the conscientious use of a checkout list is mandatory before each anesthetic procedure. A mandatory check-off procedure increases the likelihood of detecting anesthesia machine faults. Some anesthesia machines provide an automated system check that requires a variable amount of human intervention. Th ese system checks may include nitrous oxide delivery (hypoxic mixture prevention), agent delivery, mechanical and manual ventilation, pipeline pressures, scavenging, breathing circuit compliance, and gas leakage.

TABLE 4•4 Anesthesia apparatus checkout recommendations. [1,2]

This checkout, or a reasonable equivalent, should be conducted before administration of anesthesia. These recommendations are valid only for an anesthesia system that conforms to current and relevant standards and includes an ascending bellows ventilator and at least the following monitors: capnograph, pulse oximeter, oxygen analyzer, respiratory volume monitor (spirometer), and breathing-system pressure monitor with high- and low-pressure alarms. Users are encouraged to modify this guideline to accommodate differences in equipment design and variations in local clinical practice. Such local modifications should have appropriate peer review. Users should refer to the appropriate operator manuals for specific procedures and precautions.

Emergency Ventilation Equipment

* 1. Verify backup ventilation equipment is available and functioning

High-Pressure System

* 2. Check O_2 cylinder supply
- a. Open O_2 cylinder and verify at least half full (about 1000 psig).
- b. Close cylinder

* 3. Check central pipeline supplies; check that hoses are connected and pipeline gauges read about 50 psig.

Low-Pressure System

* 4. Check initial status of low-pressure system
- a. Close flow control valves and turn vaporizers off.
- b. Check fill level and tighten vaporizers' filler caps.

* 5. Perform leak check of machine low-pressure system
- a. Verify that the machine master switch and flow control valves are off.
- b. Attach suction bulb to common (fresh) gas outlet.
- c. Squeeze bulb repeatedly until fully collapsed.
- d. Verify bulb stays *fully* collapsed for at least 10 seconds.
- e. Open one vaporizer at a time and repeat steps c and d.
- f. Remove suction bulb, and reconnect fresh gas hose.

* 6. Turn on machine master switch and all other necessary electrical equipment.

* 7. Test flowmeters
- a. Adjust flow of all gases through their full range, checking for smooth operation of floats and undamaged flowtubes.
- b. Attempt to create a hypoxic O_2/N_2O mixture and verify correct changes in flow and/or alarm.

Scavenging System

* 8. Adjust and check scavenging system
- a. Ensure proper connections between the scavenging system and both APL (pop-off) valve and ventilator relief valve.
- b. Adjust waste-gas vacuum (if possible).
- c. Fully open APL valve and occlude Y-piece.
- d. With minimum O_2 flow, allow scavenger reservoir bag to collapse completely and verify that absorber pressure gauge reads about zero.
- e. With the O_2 flush activated, allow scavenger reservoir bag to distend fully, and then verify that absorber pressure gauge reads <10 cm H_2O.

Breathing System

* 9. Calibrate O_2 monitor
- a. Ensure monitor reads 21% in room air.
- b. Verify low-O_2 alarm is enabled and functioning.
- c. Reinstall sensor in circuit and flush breathing system with O_2.
- d. Verify that monitor now reads greater than 90%.

10. Check initial status breathing system
- a. Set selector switch to Bag mode.
- b. Check that breathing circuit is complete, undamaged, and unobstructed.
- c. Verify that CO_2 absorbent is adequate.
- d. Install breathing-circuit accessory equipment (eg, humidifier, PEEP valve) to be used during the case.

11. Perform leak check of the breathing system
- a. Set all gas flows to zero (or minimum).
- b. Close APL (pop-off) valve and occlude Y-piece.
- c. Pressurize breathing system to about 30 cm H_2O with O_2 flush.
- d. Ensure that pressure remains fixed for at least 10 seconds.
- e. Open APL (pop-off) valve and ensure that pressure decreases.

Manual and Automatic Ventilation Systems

12. Test ventilation systems and unidirectional valves
- a. Place a second breathing bag on Y-piece.
- b. Set appropriate ventilator parameters for next patient.
- c. Switch to automatic-ventilation (ventilator) mode.
- d. Turn ventilator on and fill bellows and breathing bag with O_2 flush.
- e. Set O_2 flow to minimum, other gas flows to zero.
- f. Verify that during inspiration bellows deliver appropriate tidal volume and that during expiration bellows fill completely.
- g. Set fresh gas flow to about 5 L min^{-1}.
- h. Verify that the ventilator bellows and simulated lungs fill and empty appropriately without sustained pressure at end expiration.
- i. Check for proper action of unidirectional valves.
- j. Exercise breathing circuit accessories to ensure proper function.
- k. Turn ventilator off and switch to manual ventilation (Bag/APL) mode.
- l. Ventilate manually and ensure inflation and deflation of artificial lungs and appropriate feel of system resistance and compliance.
- m. Remove second breathing bag from Y-piece.

(*continued*)

TABLE 4•4 Anesthesia apparatus checkout recommendations.[1,2] (continued)

Monitors	*Final Position*
13. Check, calibrate, and/or set alarm limits of all monitors: capnograph, pulse oximeter, O_2 analyzer, respiratory-volume monitor (spirometer), pressure monitor with high and low airway-pressure alarms.	14. Check final status of machine a. Vaporizers off b. APL valve open c. Selector switch to Bag mode d. All flowmeters to zero (or minimum) e. Patient suction level adequate f. Breathing system ready to use

[1] Data from http://www.fda.gov/cdrh/humfac/anesckot.html .

[2] APL, adjust pressure-limiting; PEEP, positive end-expiratory pressure.

* If an anesthesia provider uses the same machine in successive cases, these steps need not be repeated, or they can be abbreviated after the initial checkout.

DISCUSSION

Detection of a Leak

After induction of general anesthesia and intubation of a 70-kg man for elective surgery, a standing bellows ventilator is set to deliver a tidal volume of 500 mL at a rate of 10 breaths/min. Within a few minutes, the anesthesiologist notices that the bellows fails to rise to the top of its clear plastic enclosure during expiration. Shortly thereafter, the disconnect alarm is triggered.

Why has the ventilator bellows fallen and the disconnect alarm sounded?

Fresh gas flow into the breathing circuit is inadequate to maintain the circuit volume required for positive-pressure ventilation. In a situation in which there is no fresh gas flow, the volume in the breathing circuit will slowly fall because of the constant uptake of oxygen by the patient (metabolic oxygen consumption) and absorption of expired CO_2. An absence of fresh gas flow could be due to exhaustion of the hospital's oxygen supply (remember the function of the fail-safe valve) or failure to turn on the anesthesia machine's flow control valves. These possibilities can be ruled out by examining the oxygen Bourdon pressure gauge and the flowmeters. A more likely explanation is a gas leak that exceeds the rate of fresh gas flow. Leaks are particularly important in closed-circuit anesthesia.

How can the size of the leak be estimated?

When the rate of fresh gas inflow equals the rate of gas outflow, the circuit's volume will be maintained. Therefore, the size of the leak can be estimated by increasing fresh gas flows until there is no change in the height of the bellows from one expiration to the next. If the bellows collapse despite a high rate of fresh gas inflow, a complete circuit disconnection should be considered. The site of the disconnection must be determined immediately and repaired to prevent hypoxia and hypercapnia. A resuscitation bag can be used to ventilate the patient if there is a delay in correcting the situation.

Where are the most likely locations of a breathing-circuit disconnection or leak?

Frank disconnections occur most frequently between the right-angle connector and the tracheal tube, whereas leaks are most commonly traced to the base plate of the CO_2 absorber. In the intubated patient, leaks often occur in the trachea around an uncuffed tracheal tube or an inadequately filled cuff . There are numerous potential sites of disconnection or leak within the anesthesia machine and the breathing circuit, however. Every addition to the breathing circuit, such as a humidifier, increases the likelihood of a leak.

How can these leaks be detected?

Leaks usually occur before the fresh gas outlet (ie, within the anesthesia machine) or after the fresh gas inlet (ie, within the breathing circuit). Large leaks within the anesthesia machine are less common and can be ruled out by a simple test. Pinching the tubing that connects the machine's fresh gas outlet to the circuit's fresh gas inlet creates a back pressure that obstructs the forward