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TABLE 1.1 Characteristics of Commonly Used Radionuclides

	Symbol	Physical Half-Life	Approximate Energy
Photon-Emitting Radionuclides for Imaging			**Gamma (keV)**
Technetium-99m	^{99m}Tc	6 h	140
Molybdenum-99	^{99}Mo	67 h	181, 740, 780
Iodine-123	^{123}I	13.2 h	159
Iodine-131	^{131}I	8.0 days	364
Xenon-133	^{133}Xe	5.3 days	81
Gallium-67	^{67}Ga	78.3 h	93, 184, 296, 388
Indium-111	^{111}In	67 h	173, 247
Indium-113m	^{113m}In	1.7 h	392
Thallium-201	^{201}Tl	73.1 h	69, 81 (x-rays from mercury daughter)
Krypton-81m	^{81m}Kr	13 s	191
Positron-Emitting Radionuclides for Imaging			**Positron (MeV) (Image 511-keV Photons)**
Carbon-11	^{11}C	20.3 min	0.960
Nitrogen-13	^{13}N	10 min	1.198
Oxygen-15	^{15}O	124 s	1.730
Fluorine-18	^{18}F	110 min	0.634
Gallium-68	^{68}Ga	68 min	1.9
Rubidium-82	^{82}Rb	1.27 min	3.150
Unsealed Radionuclides Used for Therapy			**Emissions**
Strontium-89	^{89}Sr	50.5 days	1.46 MeV max; 0.58 MeV mean beta; 910 keV gamma (0.01%)
Yttrium-90	^{90}Y	64 h	2.2 MeV max; 0.93 MeV mean beta
Iodine-131	^{131}I	8.0 days	0.19 MeV mean beta; 364 keV gamma (82%)
Samarium-153	^{153}Sm	46 h	0.81 MeV max; 0.23 MeV mean beta; 103 keV gamma (28%)
Rhenium-186	^{186}Re	90 h	0.34 MeV mean beta; 186 keV gamma (9%)
Radium-223	^{223}Ra	11.4 days	5–7.5 MeV alpha (94%); beta 1 MeV (<4%); gamma (<2%)

Note: The approximate range (cm) of a beta particle in tissue is the energy (MeV) divided by 2.

(+7) pertechnetate (TcO_4^-). In the preparation of radiopharmaceuticals, ^{99m}Tc pertechnetate can be reduced from +7 to a lower valence state, usually +4, to permit the labeling of various chelates. This is generally accomplished with stannous (tin) ions.

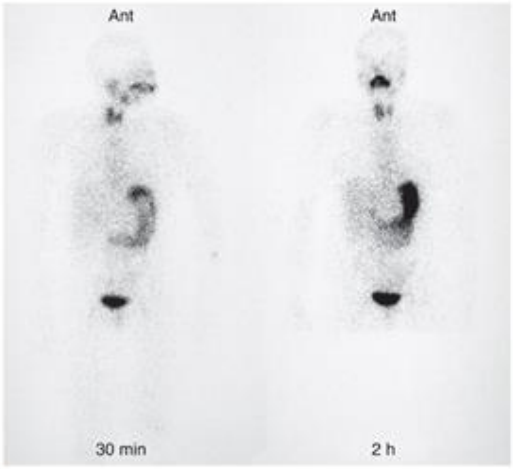
As pertechnetate, the technetium ion is a singly charged anion and is similar in size to the iodide ion. After intravenous injection, ^{99m}Tc pertechnetate is loosely bound to protein and rapidly leaves the plasma compartment. More than half leaves the plasma within several minutes and is distributed in the extracellular fluid. It rapidly concentrates in the salivary glands, choroid plexus, thyroid gland, gastric mucosa, and functioning breast tissue; during pregnancy, it crosses the placenta.

Excretion is by the gastrointestinal and renal routes. Although ^{99m}Tc pertechnetate is excreted by glomerular filtration, it is partially reabsorbed by the renal tubules; as a result, only 30% is eliminated in the urine during the first

TABLE 1.2 Characteristics of Common Positron Emission Tomography (PET) Radionuclides

Nuclide (Decay Product)	Physical Half-Life	Decay Mode	Maximal and Average Positron Energy (keV)	Maximum and Mean Range in Water (mm)	Production Reaction
Carbon-11 (Boron-11)	20.3 min	99.8% positron 0.2% electron capture	960, 385	4.1, 1.1	^{14}N(p,alpha)^{11}C*
Nitrogen-13 (Carbon-13)	10 min	100% positron	1198, 491	5.1, 1.4	^{16}O(p,alpha)^{13}N; ^{13}C(p,n)^{13}N
Oxygen-15 (Nitrogen-15)	124 s	99.9% positron	1730, 735	7.3, 1.5	^{15}N(p,n)^{15}O; ^{14}N(d,n)^{15}O
Fluorine-18 (Oxygen-18)	110 min	97% positron 3% electron capture	634, 250	2.4, 1.0	^{18}O(p,n)^{18}F; ^{20}Ne(d,alpha)^{18}F; ^{16}O(^{3}He,alpha)^{18}F
Gallium-68 (Zinc-68)	68 min	100% positron	1899	8.9, 2.9	^{68}Ge generator (T½ 271 days)
Rubidium-82 (Krypton-82)	75 s	96% positron 4% electron capture	3150, 1385	14.1, 5.9	^{82}Sr generator (T½ 25.3 days)

*This symbolism means that a proton is accelerated into an atom of nitrogen-14, causing the ejection of an alpha particle from the nucleus to produce an atom of carbon-11.



• **Fig. 1.6** Whole-Body Distribution of Technetium-99m Sodium Pertechnetate. Activity is seen in the salivary glands, thyroid gland, saliva, stomach, and bladder.

day. The ion is also secreted directly into the stomach and colon, with a much smaller amount coming from the small bowel. The colon is the critical organ and receives about 1 to 2 rad/10 mCi (0.04 mGy/MBq) of ^{99m}Tc pertechnetate administered. The biodistribution of ^{99m}Tc pertechnetate is shown in Fig. 1.6. The principal emission (140-keV photon) of ^{99m}Tc has a half-value layer (HVL) of 0.028 cm in lead and 4.5 cm in water. Because tissue is close to water in terms of attenuation characteristics, it is clear that about 2 inches of tissue between the radionuclide and the detector removes about half of the photons of interest, and 4 inches removes about three-fourths.

Iodine-123 and -131

Two isotopes of iodine (^{123}I and ^{131}I) are clinically useful for imaging and may be administered as iodide. Iodine-123 has a 13.2-hour half-life and decays by electron capture to tellurium-123 (^{123}Te). The photons emitted are 28-keV (92%) and 159-keV (84%) gamma rays. Iodine-123 is usually produced in a cyclotron by bombardment of antimony-121 (^{121}Sb) or tellurium-122 or -124 (^{122}Te or ^{124}Te). Another method is to bombard iodine-127 (^{127}I) to produce ^{123}Xe and let this decay to ^{123}I. Contamination with ^{124}I may increase the radiation dose; because ^{124}I is long lived, its proportion in an ^{123}I preparation increases with time.

Iodine-131 is a much less satisfactory isotope from an imaging viewpoint because of the high radiation dose to the thyroid and its relatively high photon energy. However, it is widely available, is relatively inexpensive, and has a relatively long shelf life. Iodine-131 has a half-life of 8.06 days and decays by beta-particle emission to a stable ^{131}Xe. The principal mean beta energy (90%) is 192 keV. Several gamma rays are also emitted, and the predominant photon is 364 keV (82% abundance) (HVL in water of 6.4 cm).

When iodine is orally administered as the iodide ion, it is readily absorbed from the gastrointestinal tract and distributed in the extracellular fluid. It is concentrated in a manner similar to that for ^{99m}Tc pertechnetate in the salivary glands, thyroid, and gastric mucosa. As with pertechnetate, there is renal filtration with significant tubular

TABLE 1.3 Imaging Radiopharmaceuticals

Radionuclide	Radiopharmaceutical	Uses
Carbon-11	Acetate	Prostate
Nitrogen-13	Ammonia	Cardiac perfusion
Oxygen-15	Gas	Brain perfusion
	Water	Metabolic agent
Fluorine-18	FDG (fluorodeoxyglucose)	Tumor, cardiac viability, brain metabolism, infection
	Sodium	Bone
	Florbetapir	Amyloid
Gallium-67	Citrate	Infection, tumor
Gallium-68	DOTATATE	Neuroendocrine tumor
Krypton-81m	Gas	Pulmonary ventilation
Rubidium-82	Chloride	Myocardial perfusion
Technetium-99m	Diphosphonate	Bone
	DISIDA (diisopropyl iminodiacetic acid)	Biliary
	DMSA (dimercaptosuccinic acid)	Renal cortical
	DTPA (diethylenetriamine pentaacetic acid)	Renal dynamic, brain, lung ventilation
	ECD (ethyl cysteinate dimmer)	Brain perfusion
	Glucoheptonate	Brain, renal dynamic
	HMPAO (hexamethylpropyleneamine oxine)	Brain perfusion
	HMPAO labeled white cells	Infection
	Labeled red cells	Gastrointestinal (GI) blood loss, cardiac function, hepatic hemangioma
	MAA (macroaggregated albumin)	Lung perfusion, LeVeen shunt patency, intraarterial liver
	MAG3 (mercaptoacetyltriglycine)	Renal
	Mebrofenin	Biliary
	Pertechnetate	Thyroid, salivary glands, Meckel diverticulum, testicular
	Sestamibi	Myocardial perfusion, parathyroid, breast
	Sulfur colloid	Liver/spleen, red bone marrow, esophageal transit, gastric emptying
	Sulfur colloid (filtered)	Lymphoscintigraphy
	Tetrofosmin	Myocardial perfusion
Indium-111	DTPA	Cerebrospinal fluid (CSF) flow, gastric liquid emptying
	Oxine labeled white cells	Infection
	Pentetreotide	Somatostatin receptor tumors
Iodine-123	Sodium	Thyroid
	MIBI (metaiodobenzylguanidine)	Pheochromocytoma, adrenal medullary, neural crest tumors
Iodine-131	Sodium	Thyroid cancer
Xenon-133	Gas	Lung ventilation
Thallium-201	Chloride	Myocardial perfusion

TABLE 1.4 Mechanisms of Localization and Examples

Capillary blockade	Macroaggregated albumin in lung
Diffusion	Filtration of DTPA by kidney
Sequestration	Leukocytes for abscess scanning
	Labeled platelets (damaged endothelium)
	Heat-damaged red blood cells for splenic scanning
Phagocytosis	Colloid scanning for liver and spleen, bone marrow, and lymph nodes
Receptor binding	Neuroreceptor imaging
Active transport	Iodocholesterol in adrenal scanning
	Iodine or pertechnetate (accumulation by choroid plexus, Meckel diverticulum, salivary gland, stomach, and thyroid)
	Technetium-99m IDA analogs in liver/biliary tract
	Orthoiodohippurate in renal tubules
	Thallous ions in myocardium
Metabolism	Fluorodeoxyglucose imaging of brain, tumor, and myocardium
Compartmental containment	Labeled red blood cells for gated blood pool studies
Compartmental leakage	Labeled red blood cells for detection of gastrointestinal bleeding
Physicochemical adsorption	Phosphate bone-scanning agents
Antibody–antigen reactions	Tumor imaging, monoclonal antibodies

DTPA, Diethylenetriaminepentaacetic acid; *IDA*, iminodiacetic acid.

reabsorption. Urinary excretion is the predominant route (35% to 75% in 24 hours), although there is some fecal excretion as well. Iodine-131 trapped and organified by the normal thyroid has an effective half-life of about 7 days. Iodine is a useful radionuclide because it is chemically reactive and is used to produce a variety of radiopharmaceuticals, which are discussed in later clinical chapters.

Xenon-133

Xenon is a relatively insoluble inert gas and is most commonly used for pulmonary ventilation studies. Xenon is commercially available in unit-dose vials or in 1 Ci (37 GBq) glass ampules. Xenon is highly soluble in oil and fat, and there is some adsorption of xenon onto plastic syringes.

Xenon-133 has a physical half-life of 5.3 days. The principal gamma photon has an energy of 81 keV and emits a 374-keV beta particle. With normal pulmonary function, its biologic half-life is about 30 seconds. Some disadvantages of ^{133}Xe include its relatively low photon energy, beta-particle emission, and some solubility in both blood and fat.

Gallium-67

Gallium-67 has a physical half-life of 78.3 hours and decays by electron capture, emitting gamma radiation. It can be produced by a variety of reactions in a cyclotron. The principal gamma photons from ^{67}Ga are 93 keV (40%), 184 keV (24%), 296 keV (22%), and 388 keV (7%). An easy way to remember these energies is to round off the figures (i.e., 90, 190, 290, and 390 keV).

When injected intravenously, most ^{67}Ga is immediately bound to plasma proteins, primarily transferrin. During the first 12 to 24 hours, excretion from the body is primarily through the kidneys, with 20% to 25% of the administered dose being excreted by 24 hours. After that time, the intestinal mucosa becomes the major route of elimination. Typically on images, activity is seen in the liver and to a lesser extent the spleen. In addition to activity within the axial skeleton, liver, spleen, and bowel, concentration is also seen in the salivary and lacrimal glands, as well as in the breasts and external genitalia. If imaging is performed in the first 24 hours, kidney and bladder activity may also be noted.

Indium-111

Indium is a metal that can be used as an iron analog; it is similar to gallium. Isotopes of interest are ^{111}In and ^{113m}In. Indium-111 has a physical half-life of 67 hours and is produced by a cyclotron. The principal photons are 173 keV (89%) and 247 keV (94%). Indium-113m can be conveniently produced by using a ^{113}Sn generator system. It has