Contrast Media's Molecular Architecture

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Understanding the elemental makeup of contrast agents benefits medical imaging and radiation therapy professionals alike, as industry data predicts worldwide growth of gadolinium- and iodine-based agents to expand from 5.23 billion U.S. dollars in 2019 to 5.42 billion U.S. dollars in 2027.[1-3] This article provides an overview of the chemistry of traditional contrast media by first examining the transition elements to benchmark the notion of energy stability via complete or half-filled orbital sublevels for electrons. Magnetic moments and paramagnetism are reviewed. Then, the lanthanides are explored, with a focus on elemental gadolinium. This subject matter prepares readers for a succinct review of molecular architecture.[4,5] Discussion concerning complex ions and chelators draws attention to the ways in which transmetallation and relaxivity influence efficacy of gadolinium-based contrast agents (GBCAs). Importantly, in keeping with themes surrounding molecular structure, the chemistry of iodinated contrast media is described.

Transition Metals

Transition metals are the largest group of elements on the periodic table and include copper, manganese, chromium, iron, cobalt, molybdenum, technetium, and tungsten among others. Manganese, cobalt, molybdenum, technetium, and tungsten are used extensively in diagnostic and therapeutic radiology (see **Table**). Appreciating the orbital relationships of transition metals helps technologists understand how the heavier and more complex metal (the lanthanide gadolinium) augments patient care.

Transition metals are in the periodic table's *d*-block, which comprises groups 3 through 12 across and periods 4 through 7 down. Here the orbital compositions begin to include a unique subshell, the *d*-orbital. What makes this subshell unique is that certain elements are afforded greater stability with lower energy costs when the *d*-orbital is completely filled or half-filled.[6] Moreover, *d*-orbitals typically are called *sublevels* because they exist energetically and spatially below the relevant outermost shell (ie, slightly below the *s*-orbitals of periods 4 through 7).

In conjunction with block-wise electron filling sequences, only after the *s*-orbital of the relevant shell (period or energy level) of the element of interest is filled will the *d*-orbital from the previous energy level begin to fill.[6] For example, the 5*s*-orbital of the fifth shell for technetium fills completely with 2 electrons before the 4*d*-orbital from the fourth shell fills with 5 electrons. This systematic ordering and filling method indicates that these *s*-orbitals, despite being farther from the nucleus, exist at relatively lower energy states when comparing the 2 orbitals (ie, the *s*- and *d*-orbitals). In general, as distance from the nucleus increases, more energy is required by atoms to keep electrons in a shell. The structure of copper (element 29) provides the perfect starting point with which to assess orbital relationships.

Table

| Photon Production, Housing, Filtering, and Collimator Materials				
Elements	Production	Housing	Filters	Collimation
Cobalt Co 60	✓			
Tungsten	✓			✓
Rhenium	✓			
Molybdenum	✓		✓	✓
Nickel	✓			
Rhodium	✓		✓	
Copper	✓		✓	
Beryllium		✓	✓	
Lead		✓		✓
Aluminum			✓	
Tin			✓	✓
Silver			✓	
Tantalum			✓	
Niobium			✓	
Erbium			✓	
Bismuth				✓
Depleted Uranium				✓

Table courtesy of the author.

Elemental Copper

Given that d-block orbitals promote up to a maximum of 5 electron pairings for a total of 10 electrons per orbital, copper's electron configuration is expressed as:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 4s^2, 3d^9$$
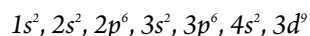
Note that the 4s-orbital, which here represents the outermost shell, exists at a lower energy state and fills first, followed by the 3d-orbital nearly backfilling completely. However, to achieve greater stability at reduced energy costs, a transaction occurs between these 2 shells. One electron is taken from the 4s-orbital (ie, the outermost orbital) and placed in the 3d-orbital (ie, the d-sublevel), which completes the d-sublevel, as follows:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 4s^1, 3d^{10}$$
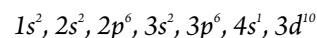
The customary way to write electron configurations for all transition metals is to place the final s-orbital at the end of the string. Therefore, switching the placement of 4s^1 and 3d^{10}, the final expression is written as:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^{10}, 4s^1$$
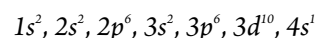
This expression depicts electrostatically neutral copper (ie, the electron count is the same as the atomic number). Note that Hund's rule, which states that 1 electron is placed into each lobe of the electron cloud before doubling up (with a maximum of 2 electrons per lobe of the orbital) was complied with.[6] Again, d-block orbitals promote up to 5 electron pairings for a total of 10 electrons per orbital.

Elemental Manganese

With a foundation laid for evaluating orbital relationships, manganese (element 25) can be better understood. The relationships between the s-orbital and d-sublevel of manganese contribute to this element's paramagnetic character. In its neutral state, manganese's final electron expression is written:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^5, 4s^2$$
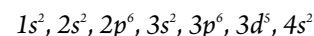
Hund's rule also is followed when the 3d-obital stops filling at its halfway point while the 4s-orbital retains its electrons. Therefore, stability and energy costs are balanced.

Elemental Chromium

Chromium (element 24) is an element that is found 1 step to the left of manganese by atomic number on the periodic table. In its neutral state, chromium's final expression is written as:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^5, 4s^1$$
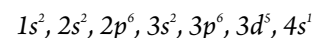
Like manganese, the d-orbital is half-filled. Unlike manganese, this half-filled status results from the theft of a 4s-orbital electron, and this theft is like the activity and pattern (in terms of reduced energy and improved stability) that occurred to complete copper's 3d-orbital. These pilfering actions make chromium's electron

configuration nearly identical to manganese because the *d*-orbitals maintain half-filled. This also demonstrates Hund's rule.

Elemental Iron

In some scenarios, transition elements require ionization reactions to balance out *s*- and *d*-orbital relationships. In addition, such transactions often modify, or further enhance, key elemental properties.[6] The ionization of iron (element 26), a ferromagnetic element, exemplifies this notion.

Adhering to Hund's rule, the expression for electrostatically neutral iron is shown by the 4*s*- and 3*d*-orbitals and is arranged as:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^6, 4s^2$$
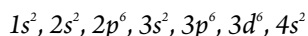
However, consider ionized iron with a +3 charge, as expressed:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^5$$
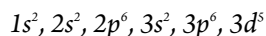
The +3 charge indicates that 3 electrons are lost (ie, 2 4*s*-orbital electrons were removed, as well as 1 electron from the 3*d*-sublevel). This loss is tracked by erasing the 4*s*-orbital (ie, iron's outermost orbital) at the end of the electron configuration chain and then subtracting 1 electron from the 3*d*-sublevel.

The result of this specific ionization state for iron (ie, the removal of 3 electrons rather than 2 electrons or 1 electron) gives the 3*d*-sublevel its half-filled status. Therefore, the ionization state makes iron more energy efficient and stable. However, exposing the 3*d*-orbital (ie, exposure of the 5 unpaired electrons) is favorable for increasing iron's magnetic susceptibility. The 3*d*-orbital now constitutes a newly acting outermost shell (ie, shell 3), allowing the magnetic moments of the 5 unpaired electrons to act unimpeded from any electrons further out.

Magnetic Moments of Electrons

According to the Pauli exclusion principle, each electron in an atom is different from its neighbor.[6] Moreover, electron up spin is +1, whereas electron down spin is −1. As a charged particle that possesses spin, electrons also possess magnetic moments. However, the inherently small electron mass generates a larger and influential magnetic moment compared with other charged particles.[6,7] For example, although protons possess spin and have identical electron values, the large proton mass (ie, 2000 times that of the electron) creates a small influential zone for the accompanying magnetic moment.[7]

The magnetic properties of paired electrons inside the lobe of an electron cloud in orbitals mathematically and physically cancel out dipole effects. This action occurs naturally from the combined results of the Pauli exclusion principle and Hund's rule, which each govern electron collections in every orbital lobe. Also, the magnetic moments of 2 or more unpaired electrons (eg, derived synergies) left unchecked cause the associated magnetism to intensify substantially. For example, the magnetic character of an element is boosted when ionizations uncover orbitals with numerous unpaired electrons in a newly acting outermost shell. This example explains the increased magnetic susceptibility of ionized iron with a +3 charge.

Paramagnetism

Paramagnetism is temporary magnetism, and it only persists when an external magnetic field is nearby. Because of this, paramagnetic elements exhibit weak attraction. Conversely, ferromagnetism is a permanent magnetism associated with strong attraction. Strong attractions are associated with magnetic resonance (MR) imaging hardware; weak attractions are associated with MR contrast agents typically based on gadolinium or manganese.[8-11]

The electron filling sequence for manganese yields 5 unpaired electrons (ie, unchecked electrons) in its *d*-orbital sublevel. However, if manganese reacts chemically and loses its outermost electrons (4*s*² electrons), then the element acquires a +2 charge and the orbital electrons in the 3*d*⁵ level assume the role as the outermost electrons. Therefore, manganese in its electrostatically neutral state is:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^5, 4s^2$$
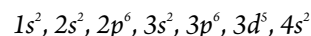
Then the following electron configuration identifies the ionized +2 state:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^5$$
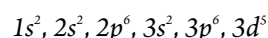
This ionization improves the energy efficiency of manganese, as well as enhances its magnetic susceptibility. Notably, the +2 ionization state is this element's most stable configuration. Manganese-enhanced MR examinations currently include anatomic studies, as well as preclinical functional and connectivity studies.[9]

Lanthanides and Gadolinium

The lanthanides represent 15 elements in the first line of the periodic table's *f*-block. This grouping is part of period 6, such that each lanthanide has 6 shells. Gadolinium (element 64), which is a heavy metal, is located midway across the lanthanides. In its electrostatically neutral state, the gadolinium atom has 8 unpaired electrons. However, the most common ionization for a lanthanide is +3, which gives gadolinium 7 unpaired electrons.[6] At body temperature, gadolinium exhibits the greatest paramagnetic effect of any element.

Overall, *f*-block orbitals promote up to 7 electron pairings for a maximum of 14 electrons per orbital. For electrostatically neutral gadolinium, the final expression for its electron order and filling sequence is shown using noble gas configuration notation:

$$[Xe]: 4f^7, 5d^1, 6s^2$$
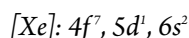
With only 1 electron in the 5*d*-orbital, the shell structure for gadolinium causes the 4*f*-orbital to hold 7 unpaired electrons—making the *f*-orbital half-filled (see **Figure 1**).

Moreover, 3 electrons are removed to obtain ionized gadolinium with a +3 charge. This means both electrons in the 6*s*-orbital are dropped succeeded by the single electron from the 5*d*-orbital. The ionization reaction is traced by erasing the 6*s*- and 5*d*-orbitals from the noble gas notation:

$$[Xe]: 4f^7$$
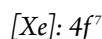
Here the paramagnetism of gadolinium becomes exceedingly influential, which explains the beneficial effect on patients who receive GBCAs during MR examinations. This ionization state produces a highly magnetic outermost orbital (ie, $4f^7$) (see **Figure 2**).

Molecular Architecture

Molecular architecture alludes to the basic principles describing chemical bonds (among and between molecules), with emphasis on the geometry and physical space of the resulting molecular makeup. Across all contrast-enhanced radiology examinations, such as cardiac MR and computed tomography angiography, the molecular structure of the contrast enhancing agent has an important role in efficacy and toxicity profiles.

Complex Ions and Chelators

A complex ion forms when a metal ion is present in solution.[11] For example, take gadolinium in water[12,13]:

$$[Gd(H_2O)_8]^{3+}$$
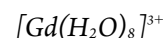
Each of the 8 water molecules comprising the gadolinium complex donate a lone pair of electrons to bond to the gadolinium ion. Moreover, each of the water molecules are called *ligand*. Ligands are molecules or ions that donate at least 1 lone pair of electrons when forming bonds with other molecules or ions.[6,14] The resulting union is called a *dative covalent bond*. However, with lanthanides, dative covalent bonds typically are called *coordinate bonds*. The binding sites distinguished on the metal also are called *coordinate sites*. Efforts to design GBCAs fall under a branch of chemistry called *coordination chemistry*.[12,14]

Gadolinium Agents in MR

Because other ligands can break apart the spherelike cage of water that surrounds the gadolinium ion, a generalized displacement reaction is expressed[12,14]:

$$[Gd(H_2O)_8]^{3+} + L_{alt} \rightleftharpoons [Gd(L_{alt})(H_2O)] + 7H_2O$$
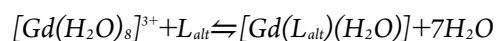
Here L_{alt} represents the alternate ligand.

Diethylenetriaminepentaacetate and dodecane tetraacetic acid are 2 alternate ligands frequently encountered in the MR examination room. Diethylenetriaminepentaacetate's structure is linear and is wrapped around the centralized gadolinium metal ion. Dodecane tetraacetic acid's geometry is macrocyclic (ie, ringlike or a large ring) and encapsulates the centralized gadolinium metal ion. The purpose of
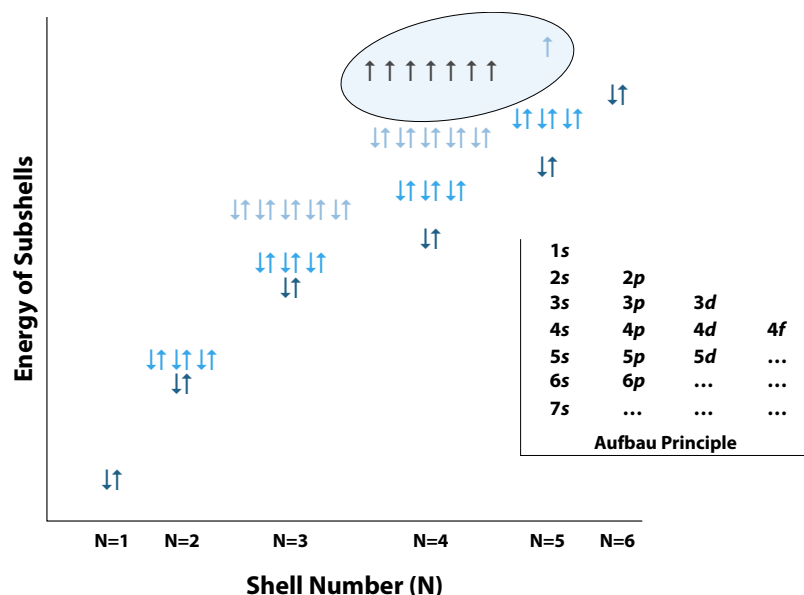
Figure 1. *The shell structure for gadolinium is depicted. To balance gadolinium's overall energy expenditures, 1 electron has been removed from the 5d orbital and placed in the 4f orbital. As a result, the 4f-orbital is half-filled with 7 electrons out of a maximal count of 14 possible orbital electrons. When considering the energy demands necessary to maintain the orbitals (ie, subshells), the 5d-orbital (ie, the 5d-sublevel) ranks highest followed by the 4f-orbital, and finally, the 6s-orbital. Image courtesy of the author.*
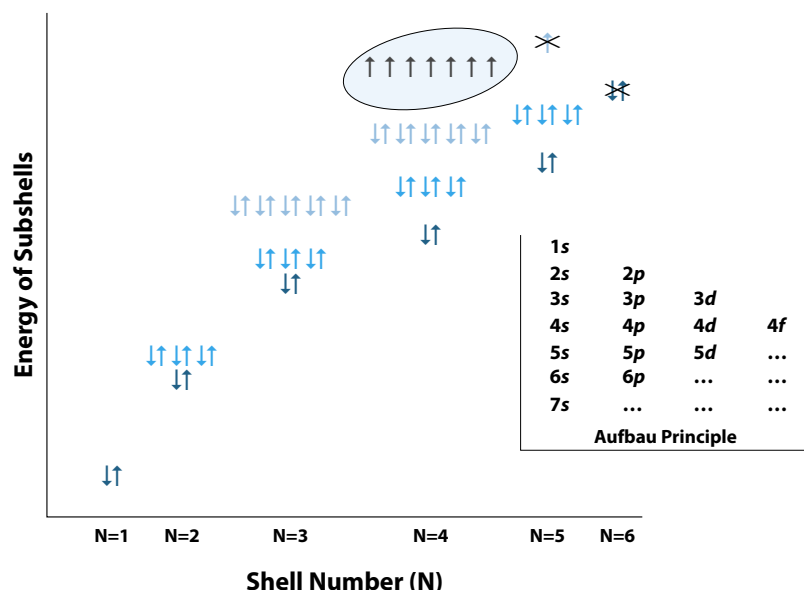
Figure 2. *Summary of the ionization process. Electron configuration for the gadolinium ion (Gd³⁺). Image courtesy of the author.*

these chelators is to protect the body by shielding tissue from the metal's toxic effects.[15]

Transmetallation vs Stability

In the human body, any roaming heavy metal (eg, free, nonchelated gadolinium) has the potential to block physiological pathways.[16] Displacement of 1 metal for another metal is called *transmetallation*. Transmetallation induces a release of gadolinium ions and can deplete the endogenous ion after its removal as a hydrophilic complex.[17]

The issue concerning gadolinium transmetallation are free, dissociated gadolinium ions being absorbed in bone and other tissues. Regarding bone, both ionized gadolinium with a +3 charge and ionized calcium with a +2 charge possess nearly equivalent ionic radii (approximately 99.0 pm or 0.99Å).[12] In 2017, investigators using x-ray fluorescence published results showing retention of gadolinium in the tibial bone as soon as participants received 1 dose of gadolinium contrast agent and up to 5 years after administration.[18] Furthermore, administered doses and gadolinium concentrations were correlated positively. Notably, gadolinium concentrations rose to 0.39 µg of gadolinium per gram of bone mineral $\pm$ 0.14 per 1 mL of contrast administered.[18]

Regarding retention of gadolinium in other tissues (independent of a patient's renal status), the brain is a primary region of interest.[19,20] In the brain, the linear chelators are more of a concern than are macrocyclic chelators.

For patients with impaired renal functions, the manifestations of gadolinium deposition in tissues can be observed clinically as nephrogenic systemic fibrosis.[21,22] Similar to the concerns

for brain tissue, linear chelators are more detrimental to kidney function than are macrocyclic chelators. Risks of developing nephrogenic systemic fibrosis are between 0.26% and 8.8% depending on several factors, including[22]:

- estimated glomerular filtration rate rates less than 15 mL · min^{-1} · 1.73 m^{-2}
- multiple MR imaging examinations with gadolinium-based contrast enhancement
- use of GBCAs at doses higher than 0.1 mmol/kg

To reduce the chances of retaining gadolinium in bones or other tissues, the manufacturers of GBCAs formulate their products around thermodynamic stability and kinetic inertness,[21,23] where kinetic inertness indicates the rate of Gd^{3+} release and thermodynamic stability describes how much Gd^{3+} is released at equilibrium under certain conditions. However, because the process to achieve equilibrium is slow, thermodynamic stability is insufficient to predict the in vivo dissociation of macrocyclic GBCAs. Furthermore, some research shows that kinetic inertness (ie, the rate of release) is the more useful predictor of in vivo Gd^{3+} release from GBCAs.[13] For instance, although the specific diseases and conditions of gadolinium deposition in brains of patients with typical renal functions and intact blood-brain barriers are uncertain, any Gd^{3+} deposited in the brain is potentially toxic.[13] Thus, studies which further exploit kinetic inertness are crucial for those seeking to develop future GBCAs.

Water and Relaxivity

Individual water molecules interact when the negative end of 1 molecule of water (ie, the oxygen side of the molecule) connects to 1 of the 2 positive hydrogen tails (ie, the 2 exposed protons associated with both hydrogens) from another water molecule. The intermolecular bonds formed between these interconnected molecular species are called *hydrogen bonds*.[6,24] Although relatively strong, the hydrogen bonds are elastic enough to be key targets during GBCA-MR examinations.[25-27] Ultimately, the gadolinium-based agents affect the dipoles of waters' exposed protons at a rate of millions of water molecules per second. Because this activity occurs at the ninth out of 9 coordinate sites associated with a gadolinium complex, this process

(called *relaxivity*) creates temporary fluctuations in the magnetic fields inherent to the exposed protons. Relaxivity contributes to gadolinium's usefulness by enacting greater signal strength and image contrast per voxel.[25,27]

Iodinated Contrast Media Chemistry

Among the 118 elements on the periodic table, iodine (element 53) has a relatively high probability for interacting with x-rays. Radii of covalently bonded iodine atoms (113 pm) are in x-ray wavelength parameters (10-10 000 pm).[28] In addition, with a binding energy of 33.2 keV, the 1s-electrons in iodine are matched for attenuating the average energy of an x-ray photon produced in the diagnostic range (see **Figure 3**).[29]

As a group 17 halogen, iodine's outermost shell (ie, shell 5) contains 7 orbital electrons. The noble gas configuration of iodine is:

$$[Kr]: 4d^{10}, 5s^2, 5p^5$$
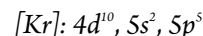
P-block orbitals promote up to 6 electrons, and thus, 1 additional electron is needed to satisfy the *octet rule*. The octet rule says that the outermost shell is stabilized when possessing 8 orbital electrons (ie, 2 electrons from the s-orbital and 6 electrons from the p-orbital). The exception is helium because it only needs 2 electrons to complete its lone shell (ie, the filled 1s^2-orbital).

All iodine-based contrast media are formulated through constraints that allow each species associated with the different agents to contain a maximum of 2 benzene molecules.[30,31] Molecular benzene consist of a ringlike structure composed of 6 covalently bonded carbon atoms. The carbon-carbon bonds alternate between double nonpolar and single nonpolar interactions. Moreover, each carbon atom also has a hydrogen atom that is held outside the ring by an additional nonpolar covalent bond. The chemical formula is C_6H_6, which makes benzene an organic compound and a hydrocarbon. When isolated, benzene is toxic and a recognized carcinogen. However, molecular benzene is rendered harmless when it serves as a primary constituent in complex chemical architecture.

To establish the benzene rings found in iodinated contrast medium, 3 out of 6 carbon-hydrogen bonds
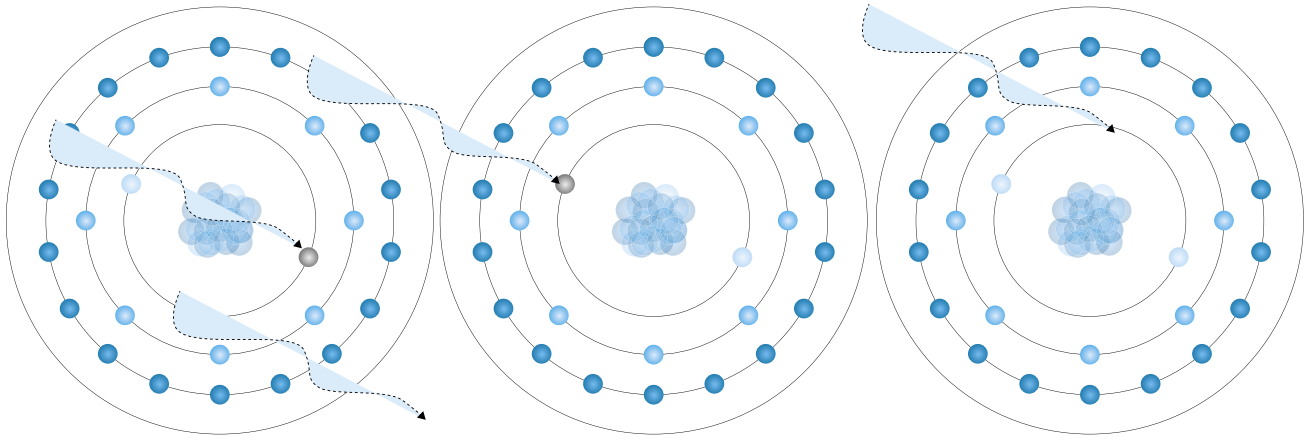
Figure 3. *A cross-sectional view of iodine atoms showing the photoelectric effect occurring in the first shell. Because the binding energy of either of the 1s-electrons for iodine is 33.2 keV, these electrons absorb the energy associated with an average diagnostic x-ray photon. This means that iodine is a well-matched contrast agent, given that millions of iodine atoms are available to block x-rays in the typical iodinated contrast medium. Image courtesy of the author.*

replace their hydrogens with iodine. This exchange occurs by means of displacement reactions using non-polar covalent bonding at positions 2, 4, and 6 on the carbon ring. Subsequently, benzene is renamed tri-iodinated benzene.

Chemical Classifications of Iodinated Contrast Media

Identifying chemical modifications placed on tri-iodinated benzene helps classify iodine-based contrast media. First, consider the ionic and nonionic features of resulting molecular species. Concerns initially arose about the number of cations and anions released into the bloodstream. Five issues manifested (and were addressed eventually) with respect to these extra ions[31]:

- disruptions in nerve conduction and cardiac muscle performance
- hemocompatibility issues
- influence on circulating electrolytes
- interference with cell membrane potential
- neurological intolerance

Another classifying scheme reflects applications of 1 tri-iodinated benzene ring vs 2 tri-iodinated benzene rings, known as *monomers* vs *dimers*, respectively.[30,31] Many of the early ionic compounds were ionic monomers (ie, each functional molecular ring contains

3 iodine atoms) and the dosing concentrations tended to be higher for these species compared with the dimers. However, when ionic species disperse into solution (ie, the bloodstream), the total number of active agents doubles because the cations and anions dissociate from each other. Considering the higher dosing concentrations, as well as the doubling effect related to the total counts of anions and cations, viscosity is high for ionic monomers.

Conversely, the development of dimers, in which each functional molecular species contains 6 iodine atoms, led to nonionic iodinated compounds. Because nonionic dimers are hydrophilic and tend not to dissociate, many of the extra ion issues were diminished or negated.[31] In addition, viscosity values also were reduced. However, because the dimer molecules are bigger molecules, viscosity comparisons are relative.

Lastly, a final classifying scheme is the effect these agents have on the osmolality of blood plasma; iodinated contrast media are categorized as high-osmolality agents, low-osmolality agents, or iso-osmolality agents.[30,31] Osmolality is the osmoles of solute in 1 kg of water (ie, solvent), whereas osmolarity is the osmoles of solute in 1 liter of solution (ie, solute and solvent combined).[32] Osmoles quantifies the dissociations of anions and cations in water.[32]

Osmolality Parity

If blood plasma has a normal osmolality of 275 through 295 osml/kg of water, then high-osmolality is regarded as 5 times that value, and low-osmolality is considered 2 through 3 times that value.[32] Moreover, the Worthley formula is the preferred method for calculating plasma's osmolality[33,34]:

$$calculated\ osmolality = 2\ (Na^+) + (glucose/18) + (BUN/2.8)$$

In this formula, Na^+ refers to the concentration of sodium ions measured in millimole per liter (mmol/L), and BUN refers to the concentration of blood urea nitrogen measured in mmol/L. Glucose concentrations are measured in mmol/L. These values can be obtained from a basic metabolic panel.

Osmolality and Viscosity of Iodinated Contrast Agents

Overall, nonionic compounds exhibit lower osmolality values because fewer amounts of active species are present. Similarly, dimers tend toward lower osmolality values. However, dimers typically have greater viscosity values because of their larger size for any given value of osmolality. The interplay between osmolality and viscosity is crucial for comparisons made between an iso-osmolalar nonionic dimer and a low-osmolalar nonionic monomer vs a high-osmolalar ionic monomer.

Iso-Osmolalar Nonionic Dimer Example

Iodixanol is a nonionic dimer and an iso-osmolalar agent. When concentrated at 320 mg/mL, the viscosity is 11.8 mPa · s at 37°C with an osmolality of 290 osml/kg, whereas concentrations at 270 mg/mL have a viscosity of 6.3 mPa · s at 37°C and an osmolality of 290 osml/kg.[31] The chemical formula is $C_{35}H_{44}I_6N_6O_{15}$.

Low-Osmolalar Nonionic Monomer Example

Iopamidol is a nonionic monomer and a low-osmolalar agent. When concentrated at 370 mg/mL the viscosity is 9.4 mPa · s at 37°C with an osmolality of 796 osml/kg, whereas concentrations at 300 mg/mL have a viscosity of 4.6 mPa · s at 37°C and an osmolality value of 630 osml/kg.[31] The chemical formula is $C_{17}H_{22}I_3N_3O_8$.

High-Osmolalar Ionic Monomer Example

Diatrizoate is an ionic monomer and a high-osmolalar agent. Concentrated at 300 mg/mL the viscosity is 2.3 mPa · s at 37°C with an osmolality of 1515 osml/kg.[31] In addition to outlining the vasculature, diatrizoate is approved for gastrointestinal imaging when the use of barium sulfate is contraindicated. Such circumstances include gastrointestinal perforation, suspected partial or incomplete stenosis, acute hemorrhage, visualized foreign bodies or gastrointestinal fistulas, and megacolon.[35] Furthermore, diatrizoate can be administered as a therapeutic agent in the treatment of certain small bowel obstructions, including outcomes that reduce the need for surgery.[36-38] Researchers theorized that in the intestinal tract high-osmolality is advantageous as an irritant that promotes peristalsis and encourages water flow into the gut which softens stool. The chemical formula is $C_{11}H_9I_3N_2O_4$.

Conclusion

Insight into the chemistry associated with contrast media permits medical imaging and radiation therapy professionals to better identify structure and mechanisms-of-action differences in next generation agents. To achieve this insight, the periodic table of the elements can be examined focusing on examples of familiar compounds found in MR, angiographic, and radiographic examination rooms. A review of select transition elements, including discussion of the magnetic moments of electrons and the factors that influence paramagnetism, is an important prerequisite for evaluation of the lanthanide gadolinium. A foundation for deconstructing the molecular architecture of GBCAs also is important. Similarly, examination of several key descriptors associated with iodinated compounds helps technologists appraise the chemistry underpinning iodine-based contrast media, including osmolality relative to these agents and blood plasma.

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Contrast Media's Molecular Architecture

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1. Which of the following identifies a permanent magnetism associated with strong attraction?
   a. Paramagnetism
   b. Ferromagnetism
   c. Diamagnetism
   d. Ferrimagnetism

2. At body temperature, _____ exhibits the greatest paramagnetic effect of any element.
   a. gadolinium
   b. lanthanum
   c. yttrium
   d. cerium

3. When ionic species disperse into solution (ie, the bloodstream), the total number of active agents _____ because the cations and anions dissociate from each other.
   a. halves
   b. quarters
   c. doubles
   d. quadruples

4. Which of the following is an example of a nonionic monomer and a low-osmolalar contrast agent?
   a. Iodixanol
   b. Iopamidol
   c. Barium
   d. Diatrizoate