Reprint from The Review of DIABETIC STUDIES

The Review Of
DIABETIC
STUDIES OPEN ACCESS

Uses of Dyes in Diagnostic Radiology

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ABSTRACT

Background: Contrast media enable the differentiation of anatomical structures and the assessment of perfusion, barrier integrity, and tissue function across several imaging modalities. The term “dye” is frequently used in clinical conversation, although iodinated agents, barium suspensions, gadolinium chelates, ultrasound microbubbles, radionuclide tracers, and fluorescent probes differ fundamentally in physics and purpose. Objective: To summarize their mechanisms, common clinical applications, safety considerations, and emerging developments. Methods: This narrative review synthesizes clinical guidelines, consensus recommendations, and selected peer-reviewed reviews; it is not a systematic review or meta-analysis. Main findings: Iodinated and barium agents increase X-ray attenuation; gadolinium agents alter MR relaxation; microbubbles enhance ultrasound signals; radiopharmaceuticals encode physiological processes through radioactive emissions; and fluorophores support optical, rather than PET, imaging. The selection of an agent should follow the clinical question, imaging modality, route of administration, and patient-specific risks. Conclusion: Rational contrast selection improves diagnostic information while minimizing preventable adverse events, unnecessary radiation, and ineffective examinations.

Keywords: contrast media; diagnostic radiology; computed tomography; magnetic resonance imaging; fluoroscopy; ultrasound; nuclear medicine; safety.

1. INTRODUCTION

Diagnostic imaging depends on differences in the interaction of tissues with X-rays, radiofrequency fields, ultrasound waves, or emitted radiation. Where intrinsic contrast is insufficient, exogenous agents can improve the conspicuity of vessels, luminal structures, inflammatory changes, and tumors. These agents are not interchangeable: radiopaque materials alter X-ray attenuation, magnetic resonance (MR) agents modify relaxation, and ultrasound microbubbles generate nonlinear acoustic signals. In nuclear medicine, the distribution of a radiotracer is itself the diagnostic signal [1–3].

In this review, the term “contrast agent” is used for substances that deliberately change the image signal, while optical fluorophores and radiopharmaceuticals are considered related but distinct diagnostic technologies. Particular attention is given to upper and lower gastrointestinal (GI) fluoroscopy, hysterosalpingography (HSG), and intravenous urography as examples of route-specific clinical applications.

2. REVIEW APPROACH

This article is a thematic narrative review, not an original clinical study or systematic review. It synthesizes selected peer-reviewed articles, consensus statements, and professional guidelines relevant

to contrast mechanisms, applications, and safety, with particular emphasis on guidance from the American College of Radiology (ACR), the European Society of Urogenital Radiology (ESUR), and radiology and nuclear medicine societies [2–4]. The synthesis is qualitative and does not claim exhaustive database coverage, formal screening or risk-of-bias assessment, or meta-analysis. Recommendations should be interpreted alongside current institutional protocols and product information.

3. CLASSES AND PHYSICAL MECHANISMS

The principal agent classes are presented in Table 1 and summarized schematically in Figure 1. Contrast enhancement does not necessarily increase spatial resolution; rather, it improves the visibility or characterization of a structure against its background. Physiologic radiotracers and fluorescence probes should not be grouped with conventional intravascular X-ray contrast because their signal-generating mechanisms are different [1,2].

Table 1. Major agent classes used in diagnostic imaging

Modality	Representative agent	Source of image contrast	Common use
X-ray / CT	Iohexol, iopamidol, iodixanol	Increased X-ray attenuation	CT angiography, enhancement
GI fluoroscopy	Barium sulfate; water-soluble iodine	Luminal opacification	Swallow, upper GI, enema
MRI	Gadobutrol, gadoterate	Changes in proton relaxation	Lesion / vascular assessment
Contrast ultrasound	Sulfur hexafluoride microbubbles	Nonlinear acoustic backscatter	Liver and vascular perfusion
PET / SPECT	[18F]FDG; 99mTc-MDP	Detectable radioactive emission	Tumor metabolism; bone scan
Optical imaging	Indocyanine green (ICG)	Near-infrared fluorescence	Perfusion / intraoperative guidance



Figure 1. Original schematic of imaging modalities and their distinct signal-generation mechanisms (not to scale).

4. RADIOPAQUE CONTRAST AGENTS

4.1 Iodinated agents for CT and angiography

Nonionic low- or iso-osmolar iodinated agents—including iohexol, iopamidol, and iodixanol—are widely used for contrast-enhanced CT, CT angiography, and selected fluoroscopic procedures. Iodine

attenuates the X-ray beam, increasing the visibility of vessels and enhancing organs in a phase-dependent manner. Intravenous injection supports evaluation of pulmonary embolism, arterial disease, infection, inflammation, solid-organ trauma, and many tumors; oral, rectal, or intracavitary delivery serves different questions. Agent choice, iodine concentration, flow rate, timing, and volume are tailored to the patient and examination [1,2].

4.2 Barium sulfate and water-soluble enteric agents

Barium sulfate suspension is used for luminal opacification in swallowing studies, upper GI series, small-bowel examinations, and selected lower GI fluoroscopic examinations. In a barium swallow the patient drinks contrast to assess the pharynx or esophagus; a barium enema introduces contrast rectally to evaluate the colon. These are distinct upper and lower GI examinations—not components of one "upper GI series." Endoscopy directly views the mucosa and permits biopsy, whereas barium fluoroscopy assesses lumen shape and dynamic transit; the procedures are complementary rather than the same test. When perforation or leak is suspected, an appropriate water-soluble iodinated agent may be preferred according to site, aspiration risk, and local protocol [2,5].

4.3 Hysterosalpingography

HSG evaluates the uterine cavity and fallopian tube patency, especially during infertility assessment. A water-soluble iodinated agent is introduced through the cervix, and fluoroscopy documents cavity contour, tubal filling, and free peritoneal spill. Findings can suggest tubal obstruction or intrauterine filling defects, but must be interpreted with clinical history and procedural limitations such as tubal spasm. Sonographic alternatives, including hysterosalpingo-contrast sonography (HyCoSy), can be considered where appropriate [6,7].

4.4 Intravenous pyelography / urography

Intravenous pyelography (IVP), also called intravenous urography (IVU), uses intravenously administered iodinated contrast followed by sequential radiographs as contrast is filtered and excreted into the collecting systems, ureters, and bladder. It historically evaluated hematuria, obstruction, and structural abnormalities. Ultrasound and CT—particularly CT urography for selected indications—have replaced IVU in many clinical pathways, although IVU may remain useful in particular settings. Examination selection should be based on clinical indication and available expertise rather than assuming IVU is routinely first line [1,2].



Figure 2. Conceptual diagrams of gastrointestinal fluoroscopy, hysterosalpingography, and intravenous urography, showing typical contrast administration routes (not to scale).

5. MAGNETIC RESONANCE CONTRAST AGENTS

Gadolinium-based contrast agents (GBCAs) are chelated paramagnetic compounds used primarily to shorten tissue T1 relaxation and enhance selected MR sequences. They support evaluation of CNS lesions, inflammation, tumor vascularity, liver lesions, and MR angiography. Common extracellular agents include gadobutrol and gadoterate; tissue-specific agents may serve specialized indications. Chelation stability, clinical indication, and renal status matter. The risk of nephrogenic systemic fibrosis has been associated particularly with older high-risk (ACR group I) agents in severe renal impairment, whereas the risk with group II agents is very low. Gadolinium retention has been documented, but retained gadolinium does not by itself establish clinically important injury [2,8,9].

6. CONTRAST-ENHANCED ULTRASOUND

Ultrasound contrast agents are micron-scale gas-filled microbubbles stabilized by lipid or protein shells. Their acoustic response permits sensitive detection of microvascular blood flow without exposing the patient to ionizing radiation. Contrast-enhanced ultrasound (CEUS) provides real-time assessment of lesion enhancement, particularly for characterization of focal liver lesions, perfusion, and selected vascular or renal indications. The agents are not equivalent to iodinated or gadolinium media and are not generally eliminated through the kidneys. Their safety profile is favorable, but rare serious hypersensitivity reactions and product-specific contraindications require preparation and appropriate supervision [2,10].

7. NUCLEAR MEDICINE AND OPTICAL IMAGING

Nuclear medicine uses radiopharmaceuticals rather than conventional "radiolabeled dyes." In single-photon emission computed tomography (SPECT), technetium-99m-labeled diphosphonates, such as 99mTc-methylene diphosphonate (MDP), localize to areas of active bone turnover. In positron emission tomography (PET), [18F]fluorodeoxyglucose ([18F]FDG) is a radiolabeled glucose analog commonly used for oncologic staging, treatment response, and selected inflammatory indications; its uptake is not tumor-specific. These agents are detected through radioactive emission, unlike fluorescent dyes [11,12]. Fluorescein and indocyanine green (ICG) emit light after optical excitation. ICG near-infrared imaging can evaluate tissue perfusion and support intraoperative visualization; fluorescein angiography is used in ophthalmology. These are optical imaging methods, not PET techniques, and their relationship to standard diagnostic radiology should be described explicitly rather than treating all labeled substances as one agent class [13].

8. SAFETY, PATIENT SELECTION, AND PRACTICAL LIMITATIONS

All contrast administration requires a clear diagnostic benefit, correct agent and route, reliable documentation of prior reactions, readiness to manage acute reactions, and attention to pregnancy, lactation, and pediatric protocols. Immediate allergic-like reactions may occur with iodinated agents, GBCAs, and microbubbles; an earlier contrast reaction is more informative than the vague label "iodine allergy." Decisions about future exposure and possible alternative agents should follow current expert guidance [2,3,14].

Acute kidney injury occurring after contrast is not necessarily caused by the agent. Consensus guidance indicates that the risk of IV iodinated contrast-induced AKI has often been overstated; patients with active AKI or advanced chronic kidney disease require individualized risk assessment and, when appropriate, preventive measures. For GBCAs, modern lower-risk agents should be selected according to current NSF classifications. Barium is inappropriate in certain suspected perforation scenarios, and aspiration risks matter for enteric contrast. These considerations cannot be reduced to a uniform warning that every contrast agent is "nephrotoxic" [2–5,8,9].

Ionizing radiation exposure is determined by the X-ray or nuclear medicine examination—not by iodinated contrast itself. Dose optimization, the appropriateness of repeated examinations, local supply, agent cost, and trained personnel remain central to safe practice. A practical workflow is to define the diagnostic question, check the contraindications and available alternatives, select the agent and route, plan acquisition timing, and document the administered substance and any adverse event.

9. DISCUSSION

The modality and contrast agent should be chosen together rather than treating "dye" administration as a generic intervention. For a suspected vascular emergency, contrast-enhanced CT may provide rapid anatomic assessment, whereas CEUS can answer selected perfusion questions without ionizing radiation. MRI contrast may be justified for lesion characterization or inflammatory assessment, and PET radiotracers contribute metabolic information that cannot be inferred from X-ray attenuation alone. In luminal examinations, the route of delivery and the possibility of leakage or aspiration can determine which enteric agent is appropriate. In HSG, a defined reproductive question and procedural safety assessment are essential. These distinctions explain why the same agent cannot be substituted across modalities [1–3,5–7,10,11].

The evidence supporting these modalities is heterogeneous. Clinical indications and agent selection are strongly influenced by patient condition, local equipment, availability, and current safety guidance; consequently, cross-modality superiority cannot be concluded from this narrative synthesis. A limitation of this review is its selective, non-systematic approach, which may omit pertinent studies and does not provide pooled estimates of diagnostic accuracy or adverse-event rates. Future comparative investigations should use clearly specified patient populations, standardized imaging outcomes, and transparent adverse-event reporting.

10. FUTURE DIRECTIONS

Investigational directions include spectral CT material characterization, high-relaxivity MR agents, molecularly targeted and nanoparticle-based probes, and quantitative CEUS or PET protocols. Some technologies remain preclinical or have restricted availability. Artificial intelligence may assist protocol planning, image reconstruction, and dose optimization, but needs prospective validation, transparent performance assessment, and clinical oversight. Development should prioritize demonstrated patient benefit, safety, accessibility, and environmental stewardship rather than signal strength alone [1,3].

11. CONCLUSION

Contrast media extend the diagnostic reach of radiology by emphasizing anatomy, vascular perfusion, or tissue physiology. Their safe use depends on matching physical mechanism and administration route to the clinical question. A precise distinction among X-ray contrast agents, MR agents, ultrasound microbubbles, radiopharmaceuticals, and optical fluorophores is essential for accurate communication, appropriate risk assessment, and high-quality imaging. Updated consensus guidance and continuing technical innovation provide a foundation for more individualized and effective diagnostic examinations.

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