Extravasation without apparent technical error in MRI: autonomic physiology and venous access stability

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Abstract

Contrast media extravasation (CMEX) is traditionally interpreted as a technical complication related to cannulation failure, venous fragility, or inappropriate injection parameters. However, in clinical practice—particularly in magnetic resonance imaging (MRI)—extravasation may occur despite apparently correct cannulation, negative low-pressure pre-injection checks, and conservative injection protocols. This article proposes an interpretive model based on autonomic physiology to explain these events.MRI represents an inherently anxiogenic environment, capable of sustaining sympathetic activation through confinement, acoustic noise, immobility, and diagnostic uncertainty. Sympathetic predominance, largely mediated by α_1-adrenergic signaling, increases peripheral venous tone and reduces effective venous compliance without structural alteration. As a result, an intravenous access that is patent under static, low-pressure conditions may become mechanically unstable during power injection, generating a static–dynamic dissociation. Because pressure requirements increase non-linearly with reductions in effective venous radius ($\Delta P \propto 1/r^4$), even modest functional narrowing can produce disproportionate pressure rises, concentrating mechanical stress at the catheter–vein interface and facilitating micro-dislodgement or focal leakage.In MRI, the frequent use of gadolinium-based contrast agents—administered in smaller volumes with favorable rheological properties—may attenuate early pain and edema, delaying clinical recognition. Recognizing patient anxiety as a procedural variable supports physiology-aware prevention strategies and real-time Stop–Check–Act decision-making based on injector pressure behavior.

Sources of evidence

Evidence was identified through targeted searches on PubMed and Google Scholar (2010–2025) using combinations of the terms extravasation, MRI, gadolinium, anxiety, sympathetic, venous compliance, and heart rate variability, supplemented by bibliography screening. Searches were last performed in 2025. Guideline documents and consensus statements on contrast media and CMEX management (ACR Manual; ESUR Guidelines; ESUR CMEX guideline) were included to support a practice-oriented interpretation and operational translation rather than to provide a formal evidence grading framework [1–3].

Introduction

CMEX is usually approached as a predominantly technical event: cannulation quality, vein condition, securement, and injector settings remain central determinants and, most of the time, they explain what happens. Yet many imaging teams recognize a recurring clinical inconsistency: extravasation occasionally occurs even when cannulation appears correct, the access yields blood return, the saline flush is easy, and the injection protocol is within typical ranges. Contemporary guidance explicitly acknowledges this possibility, noting that CMEX can occur despite appropriate precautions [3]. In MRI, reported CMEX frequency is variable across institutions and protocols, reflecting differences in patient mix, access-site visibility, and workflow timing; nonetheless, a subset of events persists even when the main technical determinants appear optimized. This article focuses on that "residual" subgroup, proposing a physiology-based explanation for why reassuring static patency checks may fail to predict dynamic instability during power injection.MRI is instructive because it often decouples access placement from injection. Cannulation and initial checks are commonly performed before the patient enters the bore, whereas contrast delivery may be delayed until multiple pre-contrast sequences are completed. Contrast flows are protocol-dependent. For hepatobiliary MRI, many sites intentionally inject more slowly (e.g., ~0.8–1.0 mL/s) to optimize arterial-phase timing; in many dynamic MRI applications, flow rates are commonly ~2–3 mL/s, while first-pass myocardial perfusion may require higher flows (~3–5 mL/s) [1,2]. Overall injected volumes are generally lower than in CT, and many GBCAs have favorable rheological and osmotic profiles [1,2,5]. Despite this, extravasation persists at variable but clinically meaningful rates [3–5]. This combination suggests that MRI contains a clinically relevant, time-dependent component: the patient's physiological state can evolve between cannulation and injection, potentially altering the mechanical behavior of an access that was initially adequate.

MRI as a stressor: why patient state can change after cannulation

MRI is not physiologically neutral. Bore confinement, gradient noise, immobility, separation from staff, and diagnostic uncertainty can amplify anxiety and sustain autonomic arousal [18,30]. In predisposed individuals—first MRI experience, claustrophobia, panic vulnerability, or high-stakes oncologic/neuro-

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logic workup—sympathetic activation may remain elevated well beyond venipuncture and continue during early scanning. From a practice standpoint, the crucial feature is not the presence of anxiety alone, but its timing. The venous access is often assessed at t_0, outside the bore, while injection may occur at t_1 after pre-contrast sequences. During this interval, autonomic balance may shift toward sympathetic predominance.Physiologically, sympathetic outflow increases noradrenaline release from postganglionic fibers and contributes to systemic catecholamine spillover [10]. Superficial upper limb veins are sympathetically innervated, and adrenergic modulation can rapidly increase venous tone at typical access sites [9]. This creates a distinction that matters in advanced imaging practice: patency does not equal compliance. An access can remain patent while becoming mechanically less adaptable to high-flow conditions [8,9]. Stress-consistent shifts are also captured by autonomic markers such as HRV, which tends to show reduced vagal indices and relative sympathetic predominance during stress [11,16,17]. Importantly, autonomic shifts can be measured inside scanner environments, and MRI-related anxiety has been linked to HRV reduction during scanning, supporting the plausibility that more anxious individuals exhibit greater autonomic drift within the bore [18,29].

Protocol-dependent timing as a modifier of venous access stability

The interval between cannulation and injection is protocol-dependent and clinically meaningful. In pelvic and lower abdominal examinations, contrast is commonly administered after completion of multiple pre-contrast sequences—typically including T2-weighted imaging in multiple planes, T1-weighted or chemical shift imaging, and diffusion-weighted imaging—resulting in a cannulation-to-injection interval that may extend to 15–20 minutes or longer depending on protocol complexity, creating both a biological and a mechanical vulnerability window. Biologically, sustained or escalating arousal inside the bore can reduce effective venous compliance. Mechanically, low-salience factors can accumulate: fixed arm posture, subtle repositioning, limb cooling, and micro-traction transmitted through tubing/connectors. Together, these can increase vulnerability at the entry point. Consequently, an access that appears reassuring at cannulation may become dynamically unstable during high-flow injection, consistent with the static–dynamic dissociation proposed here. By contrast, protocols requiring earlier contrast delivery shorten the cannulation-to-injection interval, reducing the temporal window for autonomic drift and mechanical accumulation.

Functional anatomy of upper limb veins: why site matters

Superficial upper limb veins are the most common sites for IV access in MRI. Their anatomy, wall structure, and sympathetic innervation provide the substrate through which autonomic escalation can translate into altered mechanical behavior at the catheter–vein interface.

Topographic anatomy and caliber

The dorsal venous network drains into the cephalic (radial) and basilic (ulnar) veins, connected in the cubital fossa by the median cubital vein, often selected because it is superficial and relatively fixed by perforators [25,26]. Adult basilic vein diameter at arm level averages ~6–6.5 mm, with the cephalic often slightly smaller and highly variable [26]. Distal hand and wrist veins are smaller. This matters because smaller caliber increases the pressure demand required to deliver a given flow rate.

Venous wall structure and distension reserve

Veins comprise intima, media (smooth muscle and elastic tissue), and adventitia (connective tissue and nerves) [27,28]. Although thinner than arteries, venous smooth muscle is sufficient to generate functionally meaningful contraction. Smooth muscle content varies by region; lower-limb data show greater smooth muscle proportion distally compared to proximal large veins [28]. While quantitative upper-limb data remain limited, the proximal–distal gradient supports the practical view that distal segments can be more contractile and therefore more responsive to sympathetic tone changes.

Sympathetic innervation and adrenergic responsiveness

Postganglionic sympathetic fibers travel within the venous adventitia, releasing noradrenaline that binds primarily to α_1-adrenergic receptors, triggering contraction through phospholipase C signaling and intracellular calcium mobilization [12,22]. Sympathetic activation can reduce venous diameter and shift blood from unstressed to stressed volume, thereby changing capacitance and distensibility [19–22]. Cutaneous and superficial veins are notably reactive to adrenergic modulation, including responses to cold exposure and emotional stress [6,9].

Practical implication: site selection as physiology-aware prevention

A physiology-aware interpretation supports preferential use of more proximal, larger-caliber veins (forearm/antecubital fossa) for higher-flow injections or in patients with clear arousal markers. Distal hand/wrist sites, although convenient, may offer less radius reserve and higher vasomotor responsiveness, increasing vulnerability when compliance decreases dynamically.

Proposed mechanism: venous tone, capacitance, and reduced distension reserve

Peripheral veins are capacitance vessels designed to accommodate volume changes at low pressure; their baseline compliance permits distension with modest pressure increases [8]. With sympathetic activation, venous smooth muscle tone increases and effective compliance decreases: resting lumen narrows and distension reserve shrinks, often without dramatic external signs [8,9]. Importantly, this can occur without “technical error” and without structural venous pathology. At the receptor level, α_1-adrenergic signaling is a central effector of contraction [12,13]. Calcium-sensitization pathways can sustain contraction during prolonged stress, including RhoA/ROCK-related mechanisms [14,15]. Hemodynamically, sympathetic venoconstriction reduces venous capacitance, shifting volume toward stressed compartments and maintaining pressure at the expense of diameter and distensibility [19–22]. In MRI, environmental and procedural modifiers—cold limb exposure, discomfort, prolonged immobility—may further bias toward peripheral vasoconstriction [6–9]. The clinical principle is straightforward: venous access stability is not a fixed property; it can change during the exam.

The central issue: static–dynamic dissociation during power injection

Why pre-injection checks can be “true” but insufficient

A negative pre-injection check (blood return and easy saline flush) is necessary and clinically valuable: it confirms patency and low-pressure flow. However, it does not test how the access behaves under dynamic load. During power injection, flow increases rapidly and intraluminal pressure rises [1,2]. If venous distension reserve has decreased by injection time (e.g., via autonomic escalation), failure may occur at the moment of high-flow demand even though static tests were reassuring. This mismatch is the static–dynamic dissociation.

5.2 Non-linearity of radius: the r^4 problem

For laminar flow, the Hagen–Poiseuille relationship describes the pressure gradient required to sustain flow Q along length L with viscosity μ and radius r: ΔP=8μLQϖr4\Delta P = \frac{8\mu LQ}{\pi r^4} ΔP=ϖr48μLQ

Because ΔP scales with $1/r^4$, a modest reduction in functional radius can produce a large pressure increase for the same programmed flow. While the equation assumes rigid-tube laminar flow and veins are compliant vessels with more complex behavior, the r^4 relationship remains a useful heuristic illustrating how small reductions in effective radius can translate into disproportionate pressure requirements. In vivo, local turbulence, catheter geometry, injector dynamics, and venous collapsibility further modify the relationship; nevertheless, the r^4 dependence remains an instructive sensitivity principle for understanding why modest narrowing can trigger marked pressure escalation. Practically, modest autonomic narrowing can translate into a marked injector pressure rise, concentrating stress at the catheter tip and entry point [1,5].

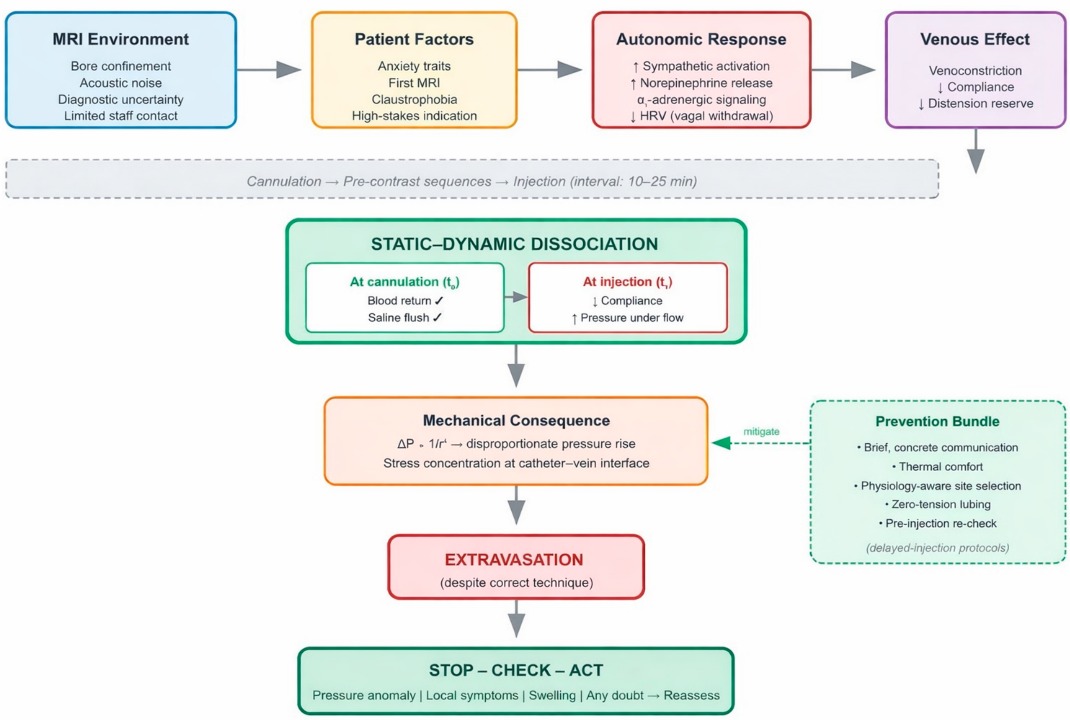

Figure 1. *Static–dynamic dissociation model for CMEX in MRI*
schematic showing how anxiety-related sympathetic activation inside the MRI bore can reduce effective venous compliance between cannulation (t_0) and injection (t_1), leading to a mismatch between negative low-pressure patency checks and instability under power injection. A modest functional reduction in effective venous radius amplifies pressure demand ($\Delta P \propto 1/r^4$), increasing mechanical stress at the catheter–vein interface and enabling micro-dislodgement or focal leakage. The model also highlights operational triggers based on injector pressure behavior and Stop–Check–Act decision-making.

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Failure trajectories compatible with correct technique

Within this model, several plausible failure pathways remain compatible with correct cannulation and negative pre-check: (i) catheter tip apposition to the venous wall as pressure rises, producing focal stress and leakage; (ii) micro-dislodgement at the entry site due to transmitted forces in a vein that cannot distend; (iii) opening of perivascular pathways created by microtrauma that is silent at low pressure but becomes relevant beyond a pressure threshold. These mechanisms align with guideline acknowledgment that CMEX may occur despite standard precautions [3].

Illustrative case: extravasation despite technically adequate access

A 55-year-old woman was referred for MRI of the lower abdomen to characterize an ultrasound finding of uncertain significance. This was her first MRI. At admission, she appeared visibly tense, expressing concern about diagnostic outcomes and anticipatory discomfort related to bore confinement. All details are anonymized, and no identifiable data are included. Venous access was established in the cephalic vein of the left proximal forearm using a 20G cannula. Blood return was confirmed and a 10 mL saline flush was performed without resistance or discomfort. The cannula was secured with a transparent dressing; the connector and extension line showed no apparent tension. The patient was positioned in the bore for pre-contrast sequences. Contrast injection occurred approximately 20 minutes after cannulation, with a programmed flow of 2.5 mL/s (conservative relative to common protocols). Within the first seconds, the injector registered a pressure rise exceeding the expected profile for that protocol and cannula gauge. The injection was stopped. The patient reported mild local tightness, and inspection revealed modest perivenous swelling consistent with limited-volume extravasation (estimated <3 mL).

Case analysis: Cannulation was technically correct, the proximal site appropriate, pre-injection check negative, securing adequate, and flow conservative. Yet extravasation occurred. During the pre-contrast interval, the patient exhibited signs consistent with sustained autonomic arousal (anxious verbalizations via intercom and repeated inquiries about remaining scan duration). The case is consistent with static–dynamic dissociation: an access patent at low pressure became unstable under flow, plausibly due to reduced venous compliance secondary to sustained sympathetic activation. The conservative flow did not prevent the event, suggesting that distension capacity, rather than absolute programmed flow alone, was critical.

Key educational points

- Pre-injection checks confirm patency, not dynamic stability under load.
- The cannulation-to-injection interval represents biological time during which autonomic state may shift.
- Conservative flows and proximal sites reduce but do not eliminate risk when venous compliance is compromised.
- Arousal signs constitute clinical indicators to integrate into risk assessment.
- Injector pressure behavior serves as an early signal of programming–response mismatch.

Technical determinants that amplify physiology (integration, not opposition)

This model is not intended to replace technical causality; it integrates it. “Extravasation without satisfactory explanation” becomes plausible when physiological drift reduces the safety margin of an access that was adequate under low-pressure conditions. Several technical determinants can compound—or unmask—this physiology-driven vulnerability in MRI, where injection may occur after a substantial interval and site observation can be limited.

Site and caliber: Distal sites provide smaller radius and less distension reserve. If compliance decreases during the scan (sympathetic venoconstriction, limb cooling), distal sites become more vulnerable for higher-flow injections [9,26]. This is not an argument against distal cannulation per se; rather, it supports physiology-aware selection: when high flow is expected or injection is delayed, more proximal veins may offer a larger “distension buffer” and reduce mechanical load at the catheter–vein interface.

Securing and micro-traction: Correct cannula placement can still be undermined if securement does not neutralize micro-traction. Small adjustments during sequences, anxiety-related muscle tension, and respiratory movement can transmit forces to the line. Instability is more likely when tubing is under tension or when cannula angle favors tip apposition to the venous wall as intraluminal pressure rises. In this interpretation, the issue may not be the puncture itself but the mechanical chain (hub–connector–extension–fixation) that transmits force to the entry point.

Cannulation-to-injection interval: MRI often introduces a longer interval between access placement and injection than other workflows. This is both “biological time” (during which compliance can change) and “mechanical time” (during which posture, cooling, and micro-traction accumulate). Delayed-injection protocols (notably pelvic/lower abdominal) therefore represent contexts where an access assessed at t_0 may benefit from deliberate reassessment immediately before injection, even if initial checks were reassuring.

Limited visibility and delayed recognition: Injection frequently occurs with reduced direct visualization of the cannulation site. This makes reliance on pain alone unsafe (Section 7) and increases the operational value of indirect signals—particularly injector

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pressure behavior relative to expected profiles.

Why gadolinium may delay recognition

Compared with iodinated agents, many GBCAs are administered in smaller volumes and have generally favorable rheology/osmolality profiles [1,2,5]. These characteristics may attenuate early pain and edema and facilitate interstitial dispersion, making early extravasation less apparent. Additionally, MRI workflows often limit direct site visualization at injection time. This creates an MRI-specific risk: CMEX can begin subtly and become evident only after several milliliters—or after injection completion. The operational conclusion is conservative and practice-relevant: absence of pain is not a reassuring criterion in MRI, and the threshold for stopping and reassessing should remain low when indirect signals emerge [3].

Table 1. *MRI stressors and protocol features linked to autonomic escalation*

Key factors	Domain
Bore confinement; gradient noise; limited staff visual contact	Environment
Prolonged immobility; delayed injection (e.g., pelvic/lower abdominal protocols)	Procedure
Claustrophobia/anxiety traits; first MRI; high-impact indication	Patient
Cold limb/low thermal comfort; discomfort/pain	Peripheral conditions

Implications for MRI practice and risk management

The most clinically actionable translation is conceptual: in MRI, anxiety is a procedural variable. It can increase after cannulation, making the injection moment more vulnerable than the access placement phase. This timing effect is protocol-sensitive. Delayed-injection protocols (pelvis/lower abdomen) create a longer window for autonomic escalation and mechanical drift; early injection workflows shorten this interval-related vulnerability.

Pragmatic-operational prevention

Brief, concrete communication: Explain when injection will occur, what sensations are expected, and which stop-signal to use. Reducing uncertainty reduces arousal. In delayed protocols, explicitly stating that contrast will be given later—after pre-contrast sequences—may reduce anticipatory anxiety.

Thermal management and limb comfort: Avoid leaving the forearm/hand cold or unnecessarily exposed; the goal is to preserve peripheral distensibility [6]. Thermal comfort is a low-cost, high-plausibility modifier of venous caliber in an anxiogenic environment.

Site selection when possible: Prefer larger, less reactive veins for high-flow protocols or in patients with arousal markers. The antecubital fossa offers anatomical advantages over distal sites [9,26], especially when injection is delayed and dynamic stability must persist over time.

Securing and "zero-tension" line: Secure the cannula and connector, reduce lever arms, eliminate tubing tension. Re-check immediately before injection in at-risk patients when cannulation-to-injection intervals are prolonged.

Operational triggers: Stop–Check–Act

To make this framework operationally useful, practical triggers must be defined. In MRI, the most actionable include:

- Unexpected pressure increase or anomalous pressure curve relative to what is expected for that protocol and access site
- New local sensation (tightness, burning, pain, "swelling") even if mild
- Visible swelling or asymmetry
- Any doubt when site visualization is limited

The response should be standardized and protective: Stop injection → Check site and line → Act (restore/new access, local management, documentation), avoiding the "push through" trap [3].

Table 2. *Triggers for immediate reassessment during MRI injection (Stop–Check–Act)*

Immediate response	Trigger
Stop → check site/line → re-site if needed	Unexpected injector pressure rise/abnormal curve
Stop → inspect/palpate → manage per protocol	New local sensation (tightness/burning/pain)
Stop → local management → document	Visible swelling/asymmetry
Stop → reassess before continuing	Any doubt with limited site visibility

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Documentation and safety culture

When CMEX is automatically equated with "error," documentation can become defensive or minimal. Yet structured documentation is clinically and organizationally valuable, supporting learning while preserving technical rigor [3]. In MRI, documentation should capture protocol timing and dynamic features central to this model: emotional state (evident anxiety yes/no), cannulation-to-injection interval, site and gauge, securement method, presence/absence of traction, pre-check and pre-injection re-check outcomes, injector pressure behavior, and the evolution of early clinical signs. These variables help reconstruct CMEX as a multifactorial interaction and promote a learning culture without lowering technical standards.

Table 3. *Minimum documentation dataset for MRI extravasation/near-miss*

Record	Item
Cannulation→injection interval (min)	Timing
Site (hand/wrist/forearm/antecubital fossa), gauge	Access
Arousal/anxiety signs (Y/N)	Patient state
Tubing tension / securement adequate (Y/N)	Mechanics
Pressure anomaly (Y/N; peak if available)	Injector

Model limitations and perspectives

This article proposes an interpretive model rather than an exclusive alternative to technical explanations. Not all MRI extravasations are explainable by autonomic physiology; vein quality, caliber, securement, line tension, cannula orientation, and injector variables remain determinants. The static–dynamic dissociation concept does not imply that pre-checks are unhelpful; it emphasizes that they are necessary but not always sufficient to predict performance under dynamic load. HRV is presented as biological plausibility support rather than an operational requirement [11,16,17,23]. The empirical grounding provided here includes a single illustrative case. While this case offers a clear example—technically optimized parameters with extravasation occurring alongside arousal markers—it does not constitute systematic validation. Prospective case series that correlate arousal indicators, injector pressure profiles, timing variables, and outcomes are needed to test predictive value and refine risk stratification. A further practical direction is evaluation of low-cost interventions as an MRI-specific prevention bundle (standardized coaching, thermal comfort, pre-injection re-check in delayed protocols, and physiology-aware site selection).

Conclusions

CMEX in MRI can occur despite correct cannulation and reassuring low-pressure pre-injection checks. A coherent explanation is the autonomic model: anxiety-related sympathetic activation can increase venous tone and reduce compliance between cannulation and injection, producing a static–dynamic dissociation in which an access adequate at low pressure becomes unstable under high-flow injection. The illustrative case—extravasation from a proximal forearm site with conservative flow and negative pre-check—exemplifies this phenomenon: when technical variables are optimized, physiological drift becomes a plausible residual determinant. Protocol-dependent timing plausibly modulates vulnerability, particularly in pelvic/lower abdominal examinations where injection is delayed, while earlier injection workflows shorten the interval-related vulnerability window. Recognizing anxiety as a procedural variable supports pragmatic mitigation measures—site selection, mechanical stability optimization, and real-time Stop–Check–Act decision-making—and reinforces a safety culture that learns from CMEX events without reducing technical standards. In MRI, physiology is part of the injector setting.

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