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From Artefact to Composite Signal: An Operational Framework for Gating Instability Management, Escalation, and Education in Cardiac MRI Radiography Practice

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Abstract

ECG-based synchronisation is routine in cardiac magnetic resonance (CMR), yet radiographers frequently encounter persistent gating instability in-bore despite correct electrode preparation. This is commonly attributed to the magnetohydrodynamic (MHD) effect, whereby conductive blood flow within the static magnetic field (B_0) generates haemodynamically induced voltages superimposed on standard depolarisation-related surface potentials. Although the biophysics of MHD is established, its operational implications for radiography workflow, quality assurance (QA) governance, and professional education have not been synthesised into a radiographer-facing framework. This paper advances three original contributions. First, the in-bore gating signal is formally characterised as a composite electro–haemodynamic measurement ($V_{measured} = V_{ECG} + V_{MHD}$), resolving the clinical paradox of persistent trigger instability despite optimal preparation. Second, a six-step radiographer-oriented escalation algorithm is proposed — from first-line setup optimisation through trigger logic tuning to alternative synchronisation strategies (Pilot Tone, Doppler ultrasound) — integrating, to the best of our knowledge, composite-signal physics, workflow escalation, QA governance, and radiography education within a single radiographer-facing framework. Third, QA governance and curriculum implications are derived, including outcome-driven metrics and AI governance considerations specific to radiography-led CMR. Treating MR-ECG as a composite measurement reframes in-bore instability as a context-dependent physical constraint, and supports an outcome-driven approach focused on timing fidelity and reduced repeat acquisitions rather than waveform normalisation.

Sources of evidence

Evidence was identified through targeted searches on PubMed and Google Scholar using combinations of the terms magnetohydrodynamic effect, cardiac MRI, ECG gating, trigger instability, pilot tone, Doppler gating, and AI R-peak detection, supplemented by bibliography screening. Searches included original research, technical reports, and clinical studies published through 2025. Sources were included if they addressed the biophysics of the MHD effect, in-bore ECG morphology, ECG-gating performance in CMR, or alternative cardiac synchronisation strategies; abstracts without retrievable methodological detail and studies focused exclusively on diagnostic ECG interpretation outside the MR environment were excluded. Pilot Tone, Doppler ultrasound, and AI-based R-peak detection were included because, within the composite-signal model, they constitute legitimate operational alternatives to conventional ECG triggering when MHD-related distortion dominates the gating channel. Key references include foundational biophysical studies on flow-induced voltages [1–3], characterisation studies of in-bore ECG distortion [4,5], QA-oriented analysis [11], and recent primary literature on AI-assisted detection and alternative synchronisation [9,10,12–14].

1.Introduction

Cardiac MRI is a timing problem before it is an image-quality problem. ECG-based synchronisation is widespread because ventricular depolarisation provides an early, repeatable marker that precedes mechanical motion. In routine clinical practice, however, radiographers frequently observe marked changes in ECG morphology as the patient enters the scanner bore. These alterations may reduce QRS salience, introduce competing deflections, and destabilise trigger markers, with operational consequences: temporal misregistration, degraded cine sharpness, increased repeat burden, and extended table time. Troubleshooting appropriately prioritises the electrode–cable acquisition chain, because extrinsic contributors — contact impedance variability, motion artefact, and cable geometry effects — are modifiable [8]. Yet a familiar plateau persists: gating may remain unreliable despite correct preparation and disciplined cable routing, suggesting that in-bore waveform alteration is not fully explained by external interference alone.

ECG alteration in MRI is primarily attributed to the magnetohydrodynamic (MHD) effect, whereby conductive blood flow interacting with (B_0) generates additional voltages detectable at the body surface [1–3]. The biophysics of this phenomenon is established in the medical physics literature, and optimisation guidance for electrode positioning exists

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[8,11]. However, the operational meaning of MHD for radiography workflow has not been translated into a practical, radiographer-facing framework. Existing literature describes MHD as an artefact to be suppressed and reports emerging technical solutions [4,5,9,10,12–14], but does not provide a structured decision pathway from first-line preparation to alternative synchronisation, nor derive QA governance and educational implications for radiography-led CMR practice. To our knowledge, no such framework currently exists in the radiography literature. Accordingly, this work is intended as a conceptual and operational framework that integrates the physical basis of the magnetohydrodynamic effect with practical workflow escalation, quality assurance governance, and radiography education in cardiac MRI.

This paper advances such a framework. Within the MR environment, the gating signal reflects both myocardial electrical activity and haemodynamically generated voltages, constituting a composite electro–haemodynamic measurement. Recognising this measurement shift supports a realistic interpretation of persistent in-bore instability and a workflow-relevant escalation strategy focused on timing extraction rather than morphology normalisation. Throughout this paper, cardiac magnetic resonance is abbreviated CMR.

2.Physical basis of the magnetohydrodynamic effect

Blood behaves as a conductive electrolyte. When conductive fluid moves within a static magnetic field, moving charges experience Lorentz forces, producing charge separation and an induced electric potential [1–3]. In the MR environment, pulsatile flow — particularly during systolic ejection in the ascending aorta — generates flow-dependent voltages that are volume-conducted to the body surface. A first-order approximation is:

$$V_{MHD} \approx B_0 \times v \times d \times \sin(\theta) \ (Equation\ 1)$$

where B_0 is the field strength, v is blood velocity, d is the effective conductive path length, and (θ) is the angle between flow direction and B_0. Equation 1 highlights clinically relevant dependencies: the MHD contribution increases with field strength and blood velocity, and is maximised when flow is perpendicular to B_0. Crucially, because this component is generated intravascularly, it is not addressable by cable management alone.

2.1 Physiological determinants and patterning

The MHD contribution varies across the cardiac cycle because it scales with blood velocity. During systole, rapid ejection increases aortic flow and the induced voltage rises; during diastole it diminishes [2,4,5]. This cycle-locked behaviour explains two common clinical observations: first, reproducible in-bore distortion patterns within the same patient; second, consistent failure modes (e.g., repeated false triggers at similar phases) rather than random instability. Inter-patient variability is expected: stroke volume, vascular compliance, and haemodynamic state can shift the relative weight of V_{MHD} .This explains why identical preparation may produce stable gating in one patient and persistent instability in another, and why repeated setup-only troubleshooting can yield diminishing returns when intrinsic, physiology-linked distortion dominates [6,7].

2.2 Spectral overlap and why filtering is insufficient

A frequent operational assumption is that MHD distortion can be filtered out to recover a clean ECG. In practice this is constrained because flow-induced components often occur at the same time and frequency as the electrical signals needed for triggering [4,5]. Aggressive filtering may attenuate the QRS complex or alter slope characteristics relied upon by detection logic, potentially worsening synchronisation. Accordingly, when MHD is prominent, instability is not best framed as a generic noise problem but as a signal composition problem: desired timing cues and confounding deflections coexist in the same channel.

3.MR-ECG as a composite electro–haemodynamic measurement

A useful operational representation of the gating signal is:

$$V_{measured} = V_{ECG} + V_{MHD} \ (Equation\ 2)$$

where Vmeasured is the waveform available to trigger logic, V_{ECG} reflects depolarisation-related surface potentials, and V_{MHD} represents the haemodynamic, flow-induced component. Equation 2 does not imply perfect separability in routine acquisition; rather, it formalises the interpretive shift required for clinical practice: the gating system operates on a composite physiological measurement whose components differ in origin and controllability. In practice, vendor-specific signal con ditioning and detection logic further modify the monitored output ($V_{measured} = f(V_{ECG} + V_{MHD})$, which explains why wave form appearance may change further beyond simple superposition. This framework is intended solely to improve synchro- nisation performance and does not imply diagnostic equivalence with a standard 12-lead ECG. In CMR, the priority is robust timing extraction rather than preserving canonical morphology. Figure 1 illustrates this contrast: the same patient exhibits stable, reliable triggering pre-bore (A) and marked composite-signal distortion in-bore (B), with the displayed RR values reflecting scanner-derived artefacts of the composite signal (see caption).

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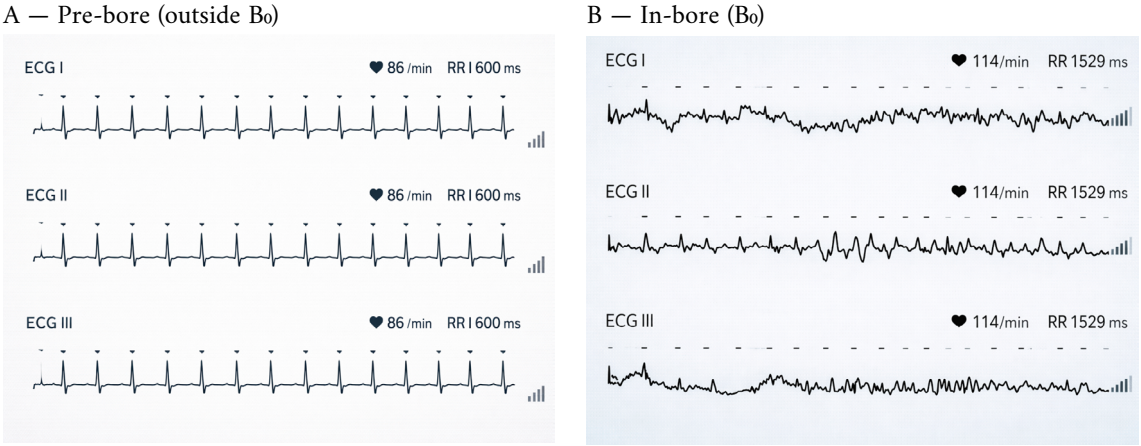


Figure 1. *Representative ECG waveforms for CMR synchronisation (leads ECG I–III), same patient. (A) Pre-bore: well-defined QRS complexes, stable trigger markers, consistent RR interval (86 bpm; 600 ms). V_{ECG} dominant; timing extraction reliable. (B) In-bore (B0): reduced QRS prominence, baseline undulation, increased signal complexity across all leads. Signal reflects the composite measurement Vmeasured = V_{ECG} + V_{MHD} (Eq. 2). In panel B the scanner monitor displays HR 114/min and RR 1529 ms; these values are mutually inconsistent (1529 ms corresponds to ~39 bpm) and should be read as scanner artefacts of the composite signal rather than physiological measurements: HR is computed over short windows that include false triggers on flow-linked deflections, while RR reflects long intervals between widely spaced detected markers (missed triggers). The patient's actual heart rate is unchanged from panel A. Repeated setup adjustment has diminishing returns; escalation of synchronisation strategy is indicated.*

4. Acquisition chain: what setup optimisation can and cannot achieve

ECG gating in CMR involves the electrode–skin interface, lead/cable transmission, monitoring/conditioning hardware, and trigger detection logic. Radiographer-controlled actions — skin preparation, electrode positioning, firm adhesion, motion minimisation, and disciplined cable routing — reduce extrinsic contributors such as impedance variability and motion artefact. These steps remain essential and should be first-line in all patients [8]. Once the patient is exposed to B_0, however, V_{MHD} is present at the electrode level and the monitoring chain conditions a composite signal without explicit source separation. This explains a common workflow plateau: repeated electrode repositioning yields marginal gains once intrinsic, haemodynamic distortion dominates. A QA principle follows directly: standardise what is controllable (preparation, electrode template, cable routing, documentation) and recognise what is intrinsic [8,11]. This prevents misattributing persistent instability to operator technique and supports structured escalation based on outcomes rather than waveform appearance.

5. Escalation framework for in-bore gating instability

Because extrinsic and intrinsic contributors can coexist, troubleshooting should follow a structured escalation rather than repeated setup cycles. The framework below translates the composite-signal model into a six-step algorithm (Box 1).

Box 1. Radiographer-Oriented Escalation Algorithm for MR-ECG Instability

- **STEP 1 – OPTIMISE:** Confirm skin preparation, electrode adhesion, and disciplined cable routing to eliminate modifiable interference. [8]
- **STEP 2 – RECOGNISE:** If morphology changes predictably upon bore entry and instability persists despite optimal setup, identify this as V_{MHD} dominance. Cease repeated setup cycles to save table time. Practical signals indicating an MHD-dominant pattern include: a morphology shift that appears on bore entry and reverses outside the bore; distortion that is reproducible and time-locked to systolic ejection (T-wave amplification or flow-linked peaks); and persistence of the same failure mode across alternative leads or VCG vectors despite verified setup. When these signs are present, further setup-only troubleshooting yields diminishing returns and the workflow should advance to Step 3. [4,5]
- **STEP 3 – ADAPT:** Adjust threshold/sensitivity and increase refractory (lockout) periods to suppress false triggers from flow-linked peaks or T-waves.
- **STEP 4 – SELECT:** Switch between available leads or vectorcardiography (VCG) vectors to identify the channel with the highest QRS salience relative to MHD deflections.
- **STEP 5 – ESCALATE:** If ECG-based triggering remains unreliable, transition to alternative methods such as Pilot Tone or Doppler ultrasound gating. It should be noted that these technologies are vendor- and platform-dependent and are not universally available across MR installations. [13,14]
- **STEP 6 – DOCUMENT:** Record patient-specific successful settings to streamline future examinations and reduce repeat rates. [11]

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5.1 Workflow-relevant endpoints

Synchronisation improvement is best assessed by performance and downstream imaging outcomes: fewer false triggers (e.g., triggering on flow-linked peaks or T-waves), fewer missed triggers and dropout events, enhanced RR stability across acquisition windows, improved cine sharpness and reduced temporal misregistration, and fewer repeat acquisitions with reduced total table time [11]. Where feasible, performance can be audited using false-trigger counts, missed-trigger proportion, RR variability (e.g., SD) over defined acquisition windows, alongside repeat rate and table time.

Table 1. *Synchronisation Strategies Under MR-ECG Alteration: Targets, Indications and Workflow Endpoints*

Strategy	What it targets	When it helps most	Availability	Operational endpoint
Setup optimisation (skin prep, electrodes, cable)	Extrinsic contamination (impedance, motion)	First-line in all patients	Universal	Fewer dropouts; improved RR stability
Trigger logic tuning (threshold/refractory)	Mis-triggering on T-wave/flow peaks	QRS present but not dominant	Universal (depth varies by vendor)	Reduced false triggers; stable markers
Lead/vector selection (multi-lead/VCG)	Maximises QRS prominence	One lead degraded, another usable	Platform-dependent	Improved trigger stability
Alternative synchronisation (Pilot Tone, Doppler US)	Reduces ECG dependence	Severe MHD dominance; persistent ECG failure	Specialist centres / new platforms	Robust triggering; fewer repeats

5.2 Clinical scenarios

The following scenarios illustrate application of the escalation framework in practice.

Box 2. Clinical Scenario 1 – When Setup Optimisation Reaches Its Limit

- **Scenario:** A 58-year-old male with preserved ejection fraction. ECG outside the bore shows normal sinus rhythm and a clear QRS. On bore entry, marked T-wave elevation appears. The radiographer repeats skin prep, repositions electrodes twice, adjusts cable routing. Morphology remains unchanged. Cine acquisition shows repeated false triggers on the T-wave.
- **Composite** framework response: Recognise V_{MHD} dominance (Step 2). Stop repeated setup cycles. Increase the refractory period (e.g., to 400 ms) to suppress T-wave triggering (Step 3). Select an alternative lead if it offers a better QRS:T ratio (Step 4). Successful acquisition achieved without further delay

Box 3. Clinical Scenario 2 – Field Strength Effect

- **Scenario:** A department upgrades from 1.5T to 3T. Several patients previously scanned successfully now show gating instability. The same radiographer uses the same protocol and electrode positions.
- **Composite framework response:** V_{MHD} scales with B_0 (Equation 1). This is expected behaviour, not a regression in technique. Update the departmental SOP to encourage earlier escalation to trigger logic tuning at 3T (Steps 3–4). Document field-specific settings for repeat patients (Step 6).

Table 2. *Common In-Bore Gating Failure Modes and Practical Radiographer Responses*

Failure Mode	Likely Mechanism	Practical Response (Escalation)	What Indicates Success
R-wave becomes small or masked	V_{MHD} dominates; QRS salience reduced	Change lead/vector; adjust sensitivity; consider alternatives	Fewer missed triggers; stable RR markers
Triggering on T-wave or flow peak	Competing peaks misidentified by trigger logic	Increase refractory/lockout; threshold tuning; lead selection	Fewer double triggers; improved cine sharpness
Persistent baseline undulation	Intrinsic low-frequency MHD component	Stop repeating setup; move to trigger logic/alternatives	Reduced table time; fewer repeats
Worse at higher field strength	Field-dependent increase in V_{MHD} amplitude	Standardise electrode positions; earlier escalation to trigger logic	Predictable workflow; fewer retries
Arrhythmia plus distortion	Rhythm variability combined with composite signal	Document rhythm; consider retrospective gating/alternatives	Reduced non-diagnostic acquisitions

6. QA governance implications for radiography-led CMR workflows

Treating MR-ECG as a composite signal reframes "ECG quality" from morphology-centric judgement to performance-governed synchronisation. Three governance principles follow. First, standardisation: controllable elements should be standardised — preparation protocol, electrode positioning template, cable routing discipline, and documentation of positioning and patient orientation — to minimise avoidable variability [8,11]. Second, recognition and management: intrinsic limitations should be recognised early and managed transparently. When in-bore distortion is reproducible and trigger fidelity remains unstable despite correct setup, repeated low-yield troubleshooting should be replaced by documented escalation. The escalation pathway (Box 1) operationalises this principle. Third, outcome-based metrics: QA evaluation should use metrics linked to image quality and workflow efficiency — false/missed trigger propensity, RR stability over defined acquisition windows, repeat rate, and total table time — rather than waveform morphology scores. These support audit and benchmarking of emerging solutions [11,16].

7. Artificial intelligence: governance in the CMR workflow

Within a composite-measurement framework, AI is most coherently viewed as a timing extractor operating on Vmeasured rather than a waveform restorer. Clinical value should be judged primarily by timing fidelity, reduced mis-triggering, and improved imaging outcomes — not by morphological similarity to an outside-magnet ECG [9,10,12,15]. Deep learning approaches have demonstrated improved robustness under MHD distortion, particularly when timing cues remain present but QRS salience is reduced [9,10,12]. However, AI approaches must be validated in real radiography workflows, with clear protocols defining when manual override is needed and who carries responsibility for gating decisions. The goal is improved timing fidelity and reduced repeats, not cleaner traces on the monitor [16]. Future development will likely benefit from physiology- and physics-aware model constraints and integration with alternative synchronisation signals.

8. Implications for education and training

Reframing MHD from "artefact" to "composite measurement" has specific implications for radiography education. Regarding curriculum: the biophysics of MHD should be taught as a standard physiological component of CMR, not merely as an artefact to be managed. The composite signal model provides a conceptual anchor that connects physical principles to clinical decision-making. Regarding simulation: training should include simulation-based scenarios to help radiographers distinguish between modifiable setup errors (random noise, baseline drift) and intrinsic MHD effects (cycle-locked distortion) [11]. Regarding competency frameworks: a distinction should be made between executive troubleshooting (applying preparation standards, Steps 1–2) and advanced decision-making (modifying trigger logic and selecting alternative strategies, Steps 3–5), consistent with broader principles of AI implementation and governance in radiography practice [16]. The following key educational points summaries the framework for teaching contexts:

- The in-bore ECG is not the same measurement as the pre-bore ECG: it is a composite of electrical and haemodynamic signals.
- Persistent trigger instability despite correct setup is a physiology-driven constraint, not a technique failure.
- Outcome-driven metrics (false triggers, RR stability, repeat rate) should guide quality assessment, not waveform morphology.
- Escalation is structured:
  OPTIMISE → RECOGNISE → ADAPT → SELECT → ESCALATE → DOCUMENT.
- Alternative synchronisation (Pilot Tone, Doppler) should be understood as a legitimate escalation pathway, not a last resort.

9. Limitations and future directions

This paper is conceptual and practice-oriented and does not include new acquisition data. MR-ECG morphology and gating performance vary with haemodynamics, anatomy, field strength, lead configuration, and vendor-specific monitoring and trigger algorithms [11]. Equations 1 and 2 are first-order operational representations intended to clarify controllability and escalation logic rather than provide comprehensive electromagnetic modelling. The escalation algorithm has not yet been formally validated in prospective studies; future work should assess its impact on table time, repeat rate, and operator decision-making consistency. Future research priorities include: radiography-aligned evaluation frameworks with standardised reporting of false/missed trigger rates and timing fidelity metrics; comparative evaluation of alternative synchronisation strategies in patients with known ECG unreliability; QA benchmarks that explicitly acknowledge the composite nature of MR-ECG signals; and AI validation across platforms, field strengths, and patient populations with governance strategies defining acceptable performance and failure modes in routine radiography workflows [9,10,12,16].

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10. Conclusions

In cardiac MRI, entry into B_0 transforms the ECG measurement context by introducing physiologically generated, flow-dependent voltages that superimpose on depolarisation-related potentials. Interpreting MR-ECG as a composite electro–haemodynamic measurement resolves the apparent contradiction between correct preparation and persistent in-bore instability, providing the conceptual basis for three original contributions: a formal composite-signal model with direct operational implications; a six-step radiographer-oriented escalation algorithm; and QA governance and educational principles specific to radiography-led CMR. This framework should inform radiography curricula and departmental protocols, shifting emphasis from morphology-dependent troubleshooting to outcome-driven escalation strategies focused on timing fidelity and reduced repeat acquisitions. Reducing repeat acquisitions not only streamlines department workflow but directly improves the patient experience by minimising in-bore time and associated anxiety.

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