

Clinical performance of implantable cardioverter-defibrillator lead monitoring diagnostics

Jeanne E. Poole, MD, FHRS,^{*} Charles D. Swerdlow, MD, FHRS,[†]
 Khaldoun G. Tarakji, MD, MPH, FHRS,[‡] Suneet Mittal, MD, FHRS,[§]
 Kenneth A. Ellenbogen, MD, FHRS,^{||} Arnold J. Greenspon, MD,[¶]
 Charles Kennergren, MD, PhD, FHRS,[#] Berit T. Philbert, MD,^{**} JoEllyn Moore, MD,^{††}
 R. Chris Jones, MD,^{‡‡} Robert D. Schaller, DO, FHRS,^{§§} Riple Hansalia, MD, FHRS,^{|||}
 Timothy Simmers, MD, PhD,^{¶¶} Attila Mihalcz, MD, PhD,^{##} Becky DeBus, MS,^{***}
 Daniel R. Lexcen, PhD,^{***} Bruce Gunderson, MS,^{***} Bruce L. Wilkoff, MD, FHRS[‡]

From the ^{}University of Washington School of Medicine, Seattle, Washington, [†]Cedars Sinai Medical Center, Los Angeles, California, [‡]Cleveland Clinic, Cleveland, Ohio, [§]Valley Health System, Ridgewood, New Jersey, ^{||}VCU School of Medicine, Richmond, Virginia, [¶]Thomas Jefferson University Hospital, Philadelphia, Pennsylvania, [#]Sahlgrenska University Hospital, Göteborg, Sweden, ^{**}Department of Cardiology, the Heart Center, Rigshospitalet, Copenhagen, Denmark, ^{††}Minneapolis Heart Institute at Abbott Northwestern Hospital, Minneapolis, Minnesota, ^{‡‡}Centennial Heart, Nashville, Tennessee, ^{§§}University of Pennsylvania, Philadelphia, Pennsylvania, ^{|||}Jersey Shore University Medical Center, Neptune, New Jersey, ^{¶¶}Catharina Ziekenhuis, Eindhoven, The Netherlands, ^{##}Universitätsklinikum Krems, Krems, Austria, and ^{***}Medtronic, Mounds View, Minnesota.*

BACKGROUND Implantable cardioverter-defibrillator (ICD) lead monitoring diagnostic alerts facilitate the diagnosis of structural lead failure.

OBJECTIVE The purpose of this study was to prospectively study the performance of Medtronic ICD lead monitoring alerts.

METHODS A prespecified ancillary substudy, World-Wide Randomized Antibiotic Envelope Infection Prevention Trial, was conducted in patients with an ICD with all available alerts enabled. The investigators reported possible lead system events (LSEs), with or without an alert. An independent committee reviewed all data and classified events as lead failure, other LSE, or nonlead event (NLE).

RESULTS In 4942 patients who were followed for 19.4 ± 8.7 months, there were 124 alerts (65 LSEs, 59 NLEs) and 19 LSEs

without an alert. Lead monitoring alerts had 100% sensitivity for the 48 adjudicated lead failures (95% confidence interval 92.6%–100%) and for 10 events adjudicated as either lead failure or connection issue. The positive predictive value of alerts for lead failure was 38.7% (48 of 124). For 34 pace-sense lead failures, an alert that incorporated oversensing was more sensitive than the pacing impedance threshold alert (33 patients [97.1%] vs 9 patients [26.5%]; $P < .0001$). However, the sensitivity was only 13.6% for lead dislodgments or perforations. Inappropriate shocks occurred in 2 patients with pace-sense lead failure (5.9%). No patient had unnecessary lead replacement for any of the NLEs.

CONCLUSION In this first real-world prospective study, lead monitoring alerts had 100% sensitivity for identifying lead failures. Although their positive predictive value was modest, no

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137 false-positive alerts resulted in an unnecessary lead replacement.
 138 Q6 For the diagnosis of pace-sense lead failure, an alert for over-
 139 sensing was more sensitive than a pacing impedance threshold
 140 alert.
 141

142 **TRIAL REGISTRATION** ClinicalTrials.gov identifier: NCT02277990;
 143
 144

145 Introduction

146 Automated, device-based, lead-monitoring alerts were devel-
 147 oped to improve the early detection of defibrillation lead fail-
 148 ure.^{1–5} In retrospective studies, alerts reduced inappropriate
 149 shocks in patients with recalled Sprint Fidelis leads⁶ and
 150 Q7 facilitated the diagnosis of lead failure in patients with other
 151 leads.^{3,7,8} No lead performance diagnostic has been studied
 152 prospectively.
 153

154 The World-Wide Randomized Antibiotic Envelope Infec-
 155 tion Prevention Trial (WRAP-IT) assessed an absorbable,
 156 antibiotic-eluting envelope for reducing infection associated
 157 with device implantations.⁹ In a prespecified ancillary study,
 158 we prospectively assessed the real-world performance of lead
 159 monitoring alerts to detect structural lead failure.
 160
 161
 162
 163

164 Methods

165 The WRAP-IT study design, patient population, and results
 166 have been reported.⁹ The protocol was approved by the ethics
 167 committee at each participating institution; all patients pro-
 168 vided written informed consent.
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 170
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 172

173 Lead monitoring study design

174 This study was prespecified as an ancillary prospective study
 175 using the WRAP-IT study patient population to assess the
 176 performance of lead monitoring alerts.
 177

178 Patient population

179 WRAP-IT patients with an implantable cardioverter-
 180 defibrillator (ICD) or cardiac resynchronization therapy–defi-
 181 brillator were enrolled. A Medtronic generator was implanted
 182 at the index WRAP-IT procedure, but leads from any manu-
 183 facturer were permitted. The investigators chose pacing and
 184 shock impedance alert thresholds, rate thresholds, and num-
 185 ber of intervals to detect ventricular tachycardia (VT) or
 186 fibrillation (VF). Only those patients with all 4 lead moni-
 187 toring alerts enabled were included in this analysis.
 188

189 Alerts included right ventricular (RV) pacing and shock
 190 impedance alerts, the Lead Integrity Alert (LIA), and the
 191 RV Lead Noise Algorithm (LNA). Impedance alerts are trig-
 192 gered for values outside a programmable range, nominally
 193 200–2000 Ω for pacing and 20–200 Ω for shock impedance.
 194 LIA is composed of 2 oversensing components and 1 abrupt
 195 impedance change component^{6,10} and is triggered when
 196 threshold criteria are satisfied for any 2 components. LNA
 197 identifies oversensing as signals on the near-field sensing
 198 channel that do not correspond to simultaneous signals on
 199 the far-field sensing channel.^{10,11} The Online Supplement
 200 describes the components of the lead monitoring diagnostic
 201 alerts in more detail.
 202
 203
 204

KEYWORDS Defibrillator; Lead diagnostics; Lead failure; Lead moni-
 205 toring; Sudden cardiac death
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 207

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 209 creativecommons.org/licenses/by/4.0/).
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215 Data collection

216 At each study visit, device data including alerts were re-
 217 viewed and reported; all suspected lead system events
 218 (LSEs) were reported, regardless of whether an alert was trig-
 219 gered. Reports included results of diagnostic tests, occur-
 220 rence of inappropriate shocks, and any action taken in
 221 response to the suspected LSE and/or alert.
 222

223 Data adjudication

224 The Lead System Events Clinical Events Committee (CEC) Q8
 225 comprised 3 physicians. Study report forms and source re-
 226 cords (eg, radiographs, procedure notes, and device interro-
 227 gation files) corresponding to each alert and all other
 228 suspected LSEs were independently reviewed to determine
 229 the root cause. Majority agreement with high confidence
 230 was required for final adjudication. Events were excluded
 231 from the analysis if no ICD interrogation data were available
 232 for analysis. An LSE was defined as an event affecting the
 233 sensing or defibrillation function of the RV defibrillation
 234 lead. The CEC used previously defined criteria based on
 235 the analysis of returned leads^{5,12,13} and/or radiography^{12,14}
 236 to adjudicate LSEs as structural lead failures or one of the
 237 following specific conditions: connection issues (between
 238 the lead pin and the header), lead perforations, or lead dis-
 239 lodgments. Findings that were used to diagnose structural
 240 lead failure were as follows: Pace-sense lead failure had to
 241 include either characteristic oversensing^{12,13,15} or abrupt
 242 impedance change *and* connection problem criteria were
 243 not fulfilled for either a DF-4 or an IS-1 connector^{4,12}. For
 244 the shock component, abrupt change in painless (subthresh-
 245 old) or shock measurement of high-voltage impedance was
 246 required *and* a connection problem was excluded. When
 247 available, radiographs showed complete insertion of the
 248 lead pin into the header.
 249

250 Events that did not meet prespecified criteria for LSEs
 251 were adjudicated as nonlead system events (NLEs). For Q9
 252 NLEs, previously reported criteria were used to determine
 253 the specific causes of impedance changes^{4,12} and oversens-
 254 ing.^{13,15} Event subcategories and diagnostic criteria for
 255 each specific event type are detailed in Online
 256 Supplemental Table 1. Online Supplemental Figures 1–13
 257 provide illustrative examples. Additionally, the CEC re-
 258 viewed all investigator-identified inappropriate shocks.
 259 However, other ICD-detected arrhythmias were not adjudi-
 260 cated.
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271 Statistical analysis

272 Standard descriptive statistics were used to summarize pa-
 273 tient characteristics. LSE detection sensitivity for each alert
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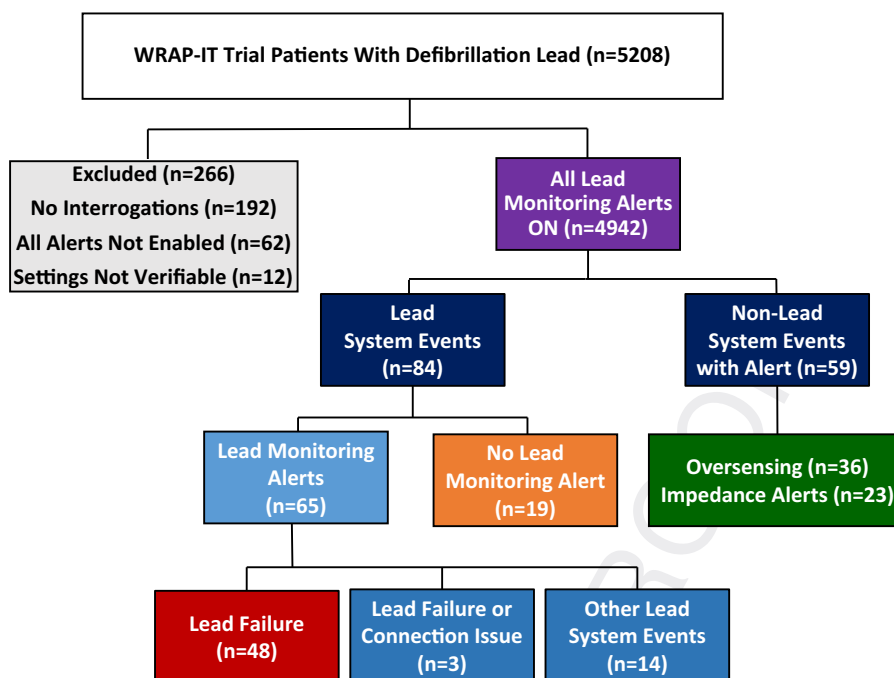


Figure 1 Summary of patient population studied. The World-Wide Randomized Antibiotic Envelope Infection Prevention Trial (WRAP-IT) enrolled 5208 patients, of whom 4942 patients had all 4 lead monitoring alerts turned on and were included in the present analysis.

was estimated as the number of LSEs detected by the alert divided by the total number of LSEs. Detection sensitivity was estimated in this manner for each type of LSE, including lead failure. The positive predictive value (PPV) of each alert for lead failure was defined as the number of lead failures detected by the alert divided by the number of alerts. Sensitivity and PPV for different alerts were compared using the χ^2 test with Yates's correction. Since lead monitoring is constantly engaged and it was assumed that leads were functioning normally in the absence of a lead issue or event, false-positive rate is a more natural metric than specificity for understanding lead monitoring alerts in the absence of lead issues. The false-positive rate at which alerts detect NLEs was estimated by dividing the total number of NLEs by the total number of lead monitoring years and expressed by the number of lead monitoring years required to observe 1 NLE.

The research reported has adhered to the Helsinki Declaration as revised in 2013.

Results

Study population

The patient population studied is shown in [Figure 1](#). An RV defibrillation lead was present in 5208 patients in the WRAP-IT. Patients were excluded from this analysis if they had no interrogation after implant ($n = 192$), any of the 4 alerts were not enabled ($n = 62$), or the status of alerts could not be verified ($n = 12$). Therefore, 4942 patients were analyzed. [Table 1](#) and [Online Supplemental Table 2](#) summarize patient and device characteristics of the study population. Patients were followed for a total of 95,685 patient-months ($19.4 \pm$

8.7 mo/patient). The average age of leads at study entry was 92.3 ± 41.9 months.

Adjudicated events

LSEs

Of the 84 LSEs, 65 triggered alerts including 48 lead failures and 17 other LSEs. Among the 17 other LSEs, the CEC could not adjudicate between lead failure and a connection issue in 3 instances. All 19 LSEs that did not trigger an alert were lead dislodgments or perforations. [Figure 2](#), [Online Supplemental Table 3](#), and [Online Supplemental Figures 1–8](#) provide further details.

Of the 48 lead failures, 34 (70.8%) involved pace-sense components, triggering oversensing and/or pacing-impedance alerts. The remaining 14 lead failures presented with shock impedance alerts. The lead manufacturer and model for the 48 lead failures is provided in [Online Supplemental Table 4](#). The dwell time at study start was 96.2 ± 39.5 months for the 28 lead failures with data available.

WRAP-IT treatment (antibiotic envelope or no envelope) had no significant effect on lead failure or LSE. Of the 84 LSEs, 36 were in the envelope arm and 48 were in the no envelope arm (42.9% vs 57.1%; $P = .1904$). Of the 48 lead failures, 18 were in the envelope arm and 30 were in the no envelope arm (37.5% vs 62.5%; $P = .0833$) ([Online Supplemental Table 2](#)).

NLEs with alerts

Of the 59 NLEs that triggered alerts, 36 were oversensing alerts and 23 were impedance alerts ([Figure 3](#)). These

Table 1 Characteristics of the study population (N = 4942)

Characteristic	Value
Age (y)	
Mean	68.4 ± 11.8
Female sex	1174 (23.8)
Medical history	
Cardiomyopathy	4098 (82.9)
Coronary artery disease	2278 (46.1)
Diabetes	1642 (33.2)
Myocardial infarction	1620 (32.8)
Renal dysfunction	823 (16.7)
COPD	667 (13.5)
Implant reason	
Generator replacement only	2768 (56.0)
New CRT system implant	1062 (21.5)
Device upgrade (with or without lead modification)	702 (14.2)
Generator replacement with lead modification	320 (6.5)
New ICD system implant*	50 (1.0)
Pocket or lead revision (no generator replacement)	40 (0.8)
RV lead origin	
Existing/chronic	3299 (66.8)
Newly implanted	1620 (32.8)
Unknown	23 (0.5)
Dual coil or single coil	
Dual coil	2859 (57.9)
Single coil	2083 (42.1)
RV lead family type initial procedure	
Medtronic	4349 (88.0)
Abbott (St. Jude Medical)	295 (6.0)
Boston Scientific	218 (4.4)
Biotronik	62 (1.3)
MicroPort (ELA Medical, Sorin Biomedica)	3 (0.1)
Unknown	15 (0.3)
RV dwell time at study start (mo) [†] (n = 2101)	92.3 ± 41.9
Any CareLink transmission	
Yes	4177 (84.5)
No	765 (15.5)
Programmed impedance thresholds (Ω)	
Pacing impedance	
Lower boundary	
200	4787 (96.9)
Unknown	155 (3.1)
Upper boundary	
1000	489 (9.9)
1500	818 (16.6)
2000	494 (10.0)
3000	2986 (60.4)
Unknown	155 (3.1)
Shock impedance	
Lower boundary	
20	4777 (96.7)
30	10 (0.2)
Unknown	155 (3.1)
Upper boundary	
100	530 (10.7)
130	786 (15.9)
160	200 (4.0)
200	3271 (66.2)
Unknown	155 (3.1)

Values are presented as mean ± SD or n (%).

COPD = chronic obstructive pulmonary disease; CRT = cardiac resynchronization therapy; ICD = implantable cardioverter-defibrillator; RV = right ventricular.

*Patients enrolled because they were planning to receive a new CRT-defibrillator, but received a new ICD instead.

[†]Implant date was not available for all chronic leads.

included oversensing alerts during VF/VT or agonal rhythm (n = 17), electromagnetic interference (n = 11), and physiologic signals (n = 8). Impedance alerts were triggered by physiologic variations in pacing or shock impedance (n = 12) or single anomalous pacing or shock impedance measurements (n = 8). Three cases were due to electrode-myocardial interface pacing impedance changes.

Performance of lead monitoring alerts

Overall performance

The sensitivity of the combined suite of all 4 lead monitoring alerts was 77.4% (95% confidence interval 67.0%–85.8%) for the 84 diagnosed LSEs and 100% (95% confidence interval 92.6%–100%) for the 48 diagnosed lead failures. The sensitivity was also 100% for the 7 connection issues and for the 3 events adjudicated as possible lead failure or connection issue. The sensitivity for lead dislodgment or perforation was 3 of 22 (13.6%). The PPV of any lead monitoring alert for lead failure was 38.7% (48 of 124 lead monitoring alerts). Overall, there was 1 true-positive alert per 166 patient-years for definite lead failure; 1 alert per 123 patient-years for any LSE; and 1 false-positive alert per 135 patient-years for any NLE (Table 2).

Performance of individual alerts

Online Supplement and Online Supplemental Table 5 describe a detailed performance of individual alerts. We emphasize 4 observations: (1) For pace-sense lead failures, LIA was more sensitive than pacing impedance (97.1% vs 26.5%; $P < .0001$) and had similar PPV (44.6% vs 50.0%; $P = .8815$). (2) When LIA was activated for lead failure, the 2 oversensing criteria were satisfied first more frequently than the abrupt impedance criterion and 1 oversensing criterion (64.7% vs 32.4%; $P = .0152$); however, the PPV was higher when the abrupt impedance criterion was satisfied (100% vs 34.9%; $P = .0002$). (3) LNA was triggered in only 9% of pace-sense lead failures and always in conjunction with LIA (Table 2). (4) The PPV of a shock impedance alert for lead failure was 33.3%. No high-voltage lead failure presented clinically. All were identified by an abrupt change in shock impedance (S6B, S6C).

Clinical considerations

Remote monitoring

Of the 124 total alerts, 112 (90.3%) occurred in patients enrolled in remote monitoring; 12 (9.7%) were in patients without remote monitoring and were detected by patient auditory alert or in-person interrogation. Of the 112 alerts in patients with remote monitoring, 81 were transmitted within 2 days (50 transmitted automatically, 31 transmitted manually in response to auditory alerts), 21 were interrogated within 2 days before any transmission occurred, and 10 were

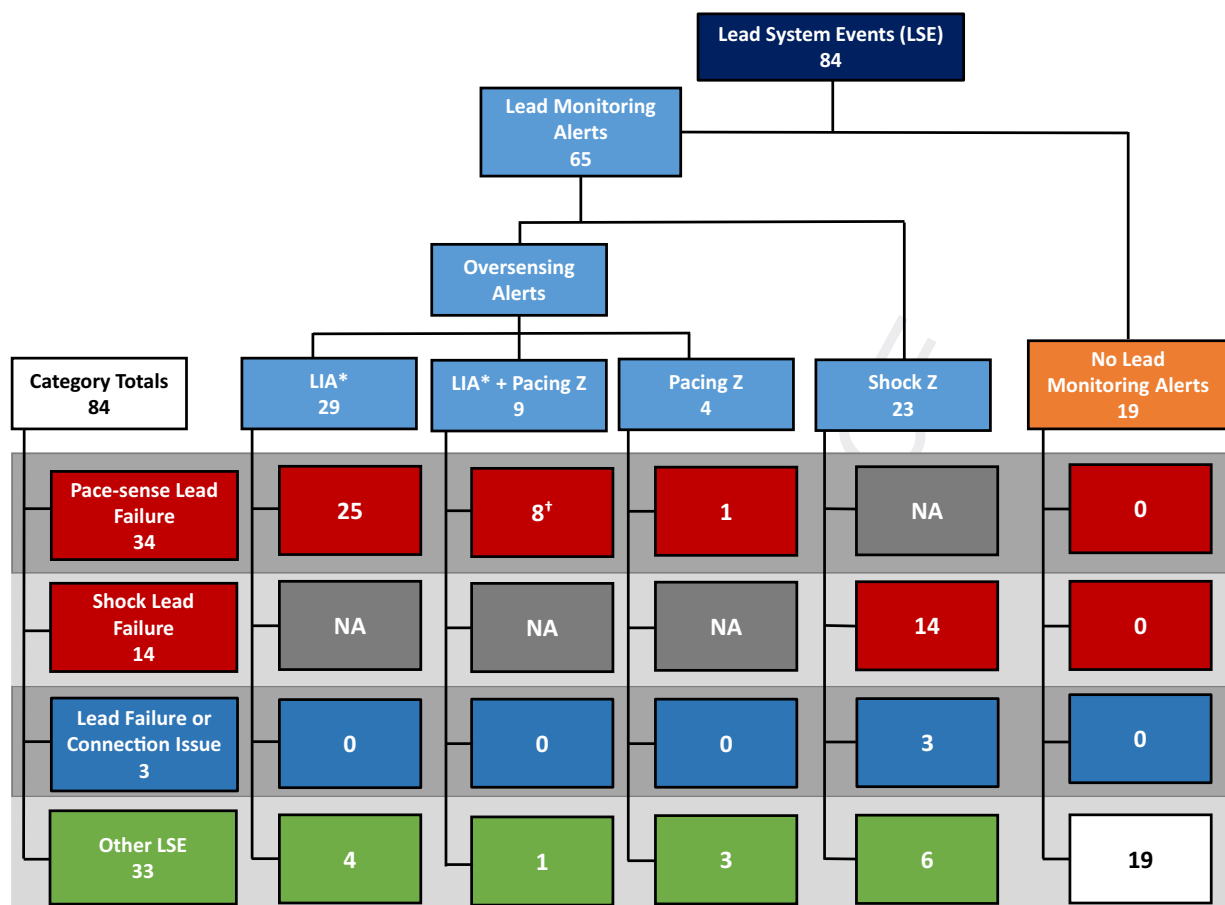


Figure 2 Lead system events (LSEs). All adjudicated LSEs are shown according to specific alert types. In 3 events, the Clinical Events Committee could not adjudicate between lead failure and connection issue. All 48 lead failures triggered an alert. All 19 LSEs that did not trigger an alert were lead dislodgments or perforations. Of the remaining 14 other LSEs, 7 were connection issues with alerts, 4 were superior vena cava (SVC) alerts in single-coil leads, and 3 were lead dislodgments or perforations. *In 4 patients with a Lead Integrity Alert (LIA), the Lead Noise Algorithm was also triggered. †In 1 patient with a single-coil lead, the SVC shock impedance (Z) alert was also triggered. NA = not applicable.

transmitted or interrogated after 2 days because of circumstances such as being out of town, not being near remote monitor, or being hospitalized at the time.

Inappropriate shocks

There were 6 inappropriate shocks in 6 patients. Three shocks for 2 pace-sense lead failures (LIA alerts), and 1 shock for a lead dislodgment to the atrium (no alert). One additional patient was shocked when LNA timed out (1 minute after LIA) and the final patient had a shock 39 hours after LIA triggered while on vacation without a remote monitor (see S4A legend for details).

Physician response to lead-monitoring alerts

Investigators replaced 37 of the 48 failed leads. One lead replacement procedure was unsuccessful, and no replacement was reported before study exit for the remaining 10 failed leads (Online Supplemental Table 6). Of the 59 NLEs with an alert, none resulted in unnecessary lead replacement. Physicians reported reprogramming for 19 of the 59 NLEs (32.2%) and no specific intervention for the remainder.

Temporal distribution of LSEs

As expected, the type of LSE that triggered lead monitoring alerts varied with the age of the lead or time after the index operation for the subset of patients for whom the date of original lead implant was available. The median time from lead implant to alert was 0.6 months for dislodgment or perforation ($n = 22$) and 107 months ($n = 28$) for lead failure. The median time from generator implant to alert for connection problem was 0.3 months ($n = 7$).

Discussion

This prespecified, prospective, ancillary study of WRAP-IT examined the real-world performance of lead monitoring alerts in a large international patient cohort. Our primary finding is that a suite of 4 alerts was 100% sensitive for clinically diagnosed, structural lead failures. Further, the rate of inappropriate shocks for both lead failures and other causes of rapid oversensing was low. Although the PPV of lead monitoring alerts was only 38.7% for lead failure, false-positive alerts triggered by events other than lead failures did not result in

		Non-Lead System Events (NLE) with a Lead Monitoring Alert 59		
Category totals		LIA* 36	Pacing Z 5	Shock Z 18
Oversensing Alerts	VT/VF 17	17	NA	NA
	EMI 11	11	NA	NA
	Oversensing of Physiologic Signals 8	8	NA	NA
Impedance Alerts	Normal Lead Physiologic Z Variation 12	NA	1	11
	Normal Lead Single Anomalous Z 8	NA	1	7
	Electrode-Myocardial Interface 3	NA	3	0

Figure 3 Nonlead system events (NLEs). All adjudicated NLEs associated with an alert are shown. *Two patients also triggered the Lead Noise Algorithm. EMI = electromagnetic interference; LIA = Lead Integrity Alert; NA = not applicable; VT/VF = ventricular tachycardia/fibrillation; Z = impedance.

unnecessary lead replacements or other adverse events and some alerted clinicians to other clinically important findings.

Individual lead-monitoring alerts

LIA

LIA, composed of both oversensing and abrupt impedance change components, was designed to provide early warning for conductor fractures and reduce inappropriate shocks.^{2,6} Subsequently, it performed well in retrospective studies of other Medtronic leads¹² and leads from multiple manufacturers.^{7,8,16}

Our prospective data confirm 3 key aspects of LIA's performance previously reported in a retrospective cohort⁷: (1) Most pace-sense lead failures are diagnosed by rapid oversensing alone without impedance alerts, (2) LIA's oversensing criteria are insensitive to the cause of rapid oversensing, resulting in a low PPV when only oversensing criteria are triggered; and (3) LIA had 100% PPV for lead failure for the few alerts in which the impedance criterion was triggered with an oversensing criterion. In a previous report, connection issues were shown to trigger LIA's impedance criterion.⁷

LNA

LNA withholds inappropriate shocks if the VF detection is otherwise satisfied by rapid oversensing^{10,11}. In our study, LNA was triggered rarely and always in conjunction with LIA, suggesting that prompt response to LIAs reduced the role of LNA. LNA's most serious potential limitation is that it could withhold lifesaving therapy, but this has never been reported to our knowledge.^{15,17} While arrhythmia events were not adjudicated in this study, we are not aware of any VT/VF event in which therapy was withheld.

Impedance alerts

Consistent with bench testing⁴ and retrospective studies,^{6,7,12,16} we found that alerts for high pacing impedance were insensitive for lead failure and had only a modest (50%) PPV. Shock impedance provides the only alert for failure of lead shock components.⁴ Bench testing and retrospective reports indicate that abrupt increases in shock impedance are sensitive for clinically significant conductor fractures or connection issue^{4,5} but decreases are insensitive for insulation breaches.^{4,18} In this prospective study, 13 shock conductor fractures were diagnosed by impedance alerts associated with abrupt impedance increases but only 1 low shock impedance alert occurred.

Table 2 Performance of lead monitoring diagnostic alerts

Variable	No. of alerts		Lead failure (n = 48)		Lead failure or connection issue (n = 3)		Connection issue (n = 7)		SVC impedance alert single-coil lead (n = 4)		Lead dislodgment or perforation (n = 22)	
	LSE (n = 65)	NLE (n = 59)	Sensitivity (%)	PPV (%)	Sensitivity (%)	PPV (%)	Sensitivity (%)	PPV (%)	Sensitivity (%)	PPV (%)	Sensitivity (%)	PPV (%)
LIA*	38	36	33/34 (97.1)	33/74 (44.6)			3/7 (42.9)				2/22 (9.1)	
Impedance Pacing	13	5	9/34 (26.5)	9/18 (50.0)			3/7 (42.9)				1/22 (4.5)	
Shock (±LIA)	24†	18	14/14 [‡] (100.0)	14/42 (33.3)	3/3 (100.0)		2/7 (28.6)		4/4 (100.0)		0/22 (0.0)	
Any alert	65	59	48/48 (100.0)	48/124 (38.7)	3/3 (100.0)		7/7 (100.0)		4/4 (100.0)		3/22 (13.6)	

LIA = Lead Integrity Alert; LNA = Lead Noise Algorithm; NLE = nonlead event; PPV = positive predictive value; RV = right ventricular; SVC = superior vena cava.

*In 4 patients with LIA, LNA was also triggered. Three were pace-sense lead failures. One was a connection issue.

†In 1 lead failure, the SVC, LIA, and shock impedance was triggered, but the patient had a single-coil lead. This patient was counted under both shock impedance and pacing impedance (±LIA).

‡Of the 14 lead failures identified by a shock impedance alert only, 3 were RV shocks, 7 were SVC shock impedance alerts, and 4 were RV shocks and SVC shocks.

Clinical implications

False-positive alerts

Some alerts triggered by causes other than lead failure provided the first warning of clinically important findings, such as connection issues and T-wave oversensing. Other alerts were not helpful, such as oversensing alerts for VT/VF and most impedance alerts in normally functioning leads. Such alerts can cause patient anxiety and burden device-monitoring clinics. Fortunately, in the present study, no physician responded to a false-positive alert by replacing a lead unnecessarily.

Inappropriate shocks

The inappropriate shock rate of 6% for pace-sense lead failures in this study was not significantly different from the rate of 12% (8 of 65) in a cohort of 12,793 lead-device combinations followed by remote monitoring for 13,562 years.⁷

Relevance to alerts from other manufacturers

While this study analyzed only Medtronic lead monitoring alerts, our primary findings should apply to all ICDs. Methods for measuring pacing and shock impedances are similar for most manufacturers,⁴ so all should be subject to the same limitations of sensitivity and PPV. Other manufacturers' oversensing diagnostics have similarities to those studied. Biotronik's RV Lead Monitoring feature is triggered by short intervals *only*. When triggered by oversensing alone, LIA has low PPV for lead failure even though it requires *both* rapid nonsustained tachycardia and short intervals. Performance has not been reported, but our data predict that this alert is sensitive but not specific. The oversensing component of Boston Scientific's Latitude Lead Check is triggered by 4 short intervals, but only within a *sustained* arrhythmia episode. It is implemented in the remote monitoring network rather than the generator; and it is the only remote monitoring "Red Alert" that is nominally off. Additionally, like LNA, Abbott's SecureSense feature identifies oversensed signals that do not correlate with electrograms on the far-field channel; but unlike LNA, SecureSense can be triggered by non-sustained events.³ Welte et al³ reported high sensitivity but low specificity.

Opportunities for improved lead-monitoring diagnostics

Our findings suggest possible improvements: we identified false-positive oversensing alerts by specific electrogram characteristics^{15,17} and false-positive impedance alerts by their impedance trend patterns.⁴ These analyses could be automated by postprocessing source data for existing alerts in a programmer or remote monitoring network before they are presented to the clinician. Remote monitoring facilitates rapid transmission of alerts for prompt intervention, and opportunities to maximize its use are important.^{16,19} Our findings also highlight the need for new diagnostics for lead dislodgment or perforation.^{14,20} Additionally, previous work has established the insensitivity of shock impedance

for potentially catastrophic insulation breaches and proposed novel diagnostics to overcome this limitation.^{4,18}

Study limitations

This study has 2 fundamental limitations common to clinical studies of lead failure. First, we could only identify lead failures if they triggered alerts or presented with clinical evidence of lead dysfunction, such as abnormal impedance on a delivered shock or failure to capture. Neither this study nor other clinical studies of lead failure could identify sub-clinical failures that did not trigger alerts or present clinically. A second fundamental limitation is that no lead diagnosed as having failed was returned for analysis, so we could not confirm diagnoses. However, the diagnostic criteria we used were based on rigorous studies in which leads were returned for analysis (Online Supplemental Table 1).^{5,12,13} Characteristic oversensing patterns are considered diagnostic of lead failure or connection issue^{12,13}; these occurred in 33 of 34 pace-sense lead failures. Subthreshold impedance or impedance during delivered shocks are the primary clinical measures of shock component integrity. The limitation of subthreshold measurements for underdiagnosis of insulation breaches is widely acknowledged,^{4,18,21} but most leads in this study were Medtronic leads, which have a low incidence of insulation breaches. For shock conductor fracture, the abrupt impedance increase criterion we used was validated by returned-product analysis⁵ and did not occur in any of the 7796 functioning Medtronic leads in a recent analysis.⁴ In analyzing alerts, it is not always possible to distinguish lead conductor fracture from connection issues because both may cause abrupt increases in impedance.^{12,13} Thus, we adjudicated 3 alerts as LSEs caused by either conductor fracture or connection issue.

We excluded patients who did not have device interrogations and followed patients only to their last interrogation or last available contact point, so it is unlikely that we missed clinical evidence of lead system malfunction that did not trigger an alert. Patients were followed for a mean of only 19.4 months, but many leads were at risk of failure, since the average age of leads, when known, at study entry was 92.3 ± 41.9 months. In comparison with an unselected population, our cohort comprised primarily Medtronic leads,¹² which are more prone to conductor fracture than insulation breach, and a higher proportion of older leads after generator change than new leads after the initial implant.

Conclusion

In this first prospective international study, lead monitoring alerts were 100% sensitive for clinically diagnosed, structural lead failures. Use of all lead monitoring alerts was associated with a low rate of inappropriate shocks. For pace-sense lead failure, an alert that incorporates oversensing was more sensitive than an impedance threshold alert and had a comparable PPV. Although the overall PPV of lead monitoring alerts

was modest, false-positive alerts were rare and did not result in unnecessary lead replacements or other adverse events.

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Appendix Supplementary data

Supplementary data associated with this article can be found in the online version at <https://doi.org/10.1016/j.hrthm.2021.10.032>.

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