REVIEW ARTICLE

Electrical Storm in Patients with an Implanted Defibrillator: A Matter of Definition

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The term "electrical storm" (ES) indicates a state of cardiac electrical instability manifested by several episodes of ventricular tachyarrhythmias (VTs) within a short time. In patients with an implantable cardioverter defibrillator (ICD), ES is best defined as 3 appropriate VT detections in 24 h, treated by antitachycardia pacing, shock or eventually untreated but sustained in a VT monitoring zone. The number of shocks and inappropriate detections are irrelevant for the definition. ES occurs in approximately 25% of ICD patients within 3 years, with typically 5–55 individual VTs within one storm. Potential triggers can be found in approximately 66% of patients and include new/worsened heart failure, changes in antiarrhythmic medication, context with other illness, psychological stress, diarrhea, and hypokalemia. In most patients, ES consists of monomorphic VT indicating the presence of reentry while ventricular fibrillation indicating acute ischemia is rare. ES seems to have a low immediate mortality (1%) but frequently (50–80%) leads to hospitalization. Long-term prognostic implications of ES are unclear. The key intervention in ES is reduction of the elevated sympathetic tone by beta blockers and frequently benzodiazepines. Amiodarone i.v. has also been successful and azimilide seems promising while class I antiarrhythmic drugs are usually unsuccessful. Substrate mapping and VT ablation may be useful in treatment and prevention of ES. Prevention of ES requires ICD programming systematically avoiding unnecessary shocks (long VT detection, antitachycardia pacing where ever possible) which otherwise can fuel the sympathetic tone and prolong ES.

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The term "electrical storm" was introduced in the early 1990s to indicate a state of cardiac electrical instability manifested by several episodes of ventricular tachyarrhythmias (VTs) within a relatively short time.[1] This implied a serious mortality risk (80–90%),[2,3] and a condition requiring intensive care, hemodynamic interventions, (multiple) external cardioversions, and frequent resuscitation.

Patients with an implantable cardioverter defibrillator (ICD) are at a particular risk to develop electrical storm because they typically have a severely reduced left ventricular function and in the case of ICDs for secondary prevention a history of previous VT. However, the prognosis of electrical storm in ICD patients—where the device quickly terminates VTs—is not clear. The ICD may render electrical storm a rather harmless event or the situation carries a crucial risk when the underlying cause (e.g. ischemia, worsening of heart failure) is not treated. Electrical storm in ICD patients may still be associated with increased mortality, either immediately due to intractable VT (sudden death in ICD patients),[4] or as a predictor of impaired long-term prognosis.

In the decade between 1996 and 2006, a number of studies have analyzed the incidence and prognostic implications of electrical storm in ICD patients (Table 1).

Definition of Electrical Storm

In patients without an ICD, electrical storm has been defined as the occurrence of "≥ 2 hemodynamically destabilizing VTs in 24 hour,"[10]

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Table 1. Definition, Incidence and Prognostic Implications of Electrical Storm

Author	ES Definition	ES Incidence (patients)	ES Prognosis	Remarks
Kowey[10]	≥2 hemo-dynamically relevant VT in 24 hour	(All patients)	↓ (Mortality 13.6% in 48 hour)	AAD study with ES as inclusion criterion
Villacastin[5]	≥2 shocks for one VT episode	16/80 (20%)	↓	DFT ?
Fries[9]	≥2 VT separated by ≤ 1 hour SR	34/57 (60%)	↓	Post implant VT included
Credner[18]	≥3 VT in 24 hour	14/136 (10%)	Ø	Only treated VT
Nademanee[17]	≥20 VT in 24 hour or ≥4 VT in 1 hour	(All patients)	↓ (1-year mortality 95% on AAD and 33% on β blocker)	Study on AAD versus β blocker in ES
Exner[12]	≥3 VT in 24 hour	90/457 (20%)	↓ (RR 2.4)	Only treated VT
Greene[19]	≥3 VT in 24 hour	40/227 (18%)	Ø	Only treated VT
Bänsch[15]	≥3 VT in 24 hour	30/106 (28%)	↓	Only DCM
Verma[23]	≥2 VT requiring shock in 24 hour	208/2028 (10%)	↓	
Wood[7]	≥3 VT in 24 hour	50/521 (9.5%)	(Not analyzed)	
Stuber[16]	≥3 VT in 2 weeks	51/214 (24%)	↓: 5 year mortality 33 versus 13%	Only treated VT
Hohnloser[20]	≥3 separate VT in 24 hour	148/633 (23%)	Ø	Treatment with azimilide; all patients had had VT before
Arya[38]	≥3 VT in 24 hour	22/162 (14%)	NA	
Brigadeau[39]	≥2 separate VT in 24 hour	123/307 (40%)	Ø	
Gatzoulis[40]	≥3 VT in 24 hour	32/169 (19%)	↓: Mortality 53 versus 14% during 33 ± 26 months	

The studies by Kowey et al.[10] and Nademanee et al.[17] included patients without an ICD. AAD = antiarrhythmic drugs, DCM = dilative cardiomyopathy; DFT = defibrillation threshold; ES = electrical storm; RR = relative risk; SR = sinus rhythm; vs = versus; VT = ventricular tachyarrhythmia; Ø = no influence on prognosis; ↓ = reduced prognosis.

(Table 1). In contrast, it has also been defined as "≥ 20 VTs in 24 hour or ≥ 4 VTs in 1 hour" in a study on antiarrhythmic drugs versus beta-blocker therapy,[17] as "VT recurring immediately after termination,"[10] "VT for at least one half of each of 3 days",[13] and as "sustained and non-sustained tachycardia resulting in total ventricular ectopic beats in 24 hour more than total sinus beats."[14]

In ICD patients, hemodynamic instability is not part of the definition as arrhythmias are usually terminated within seconds before causing hemodynamic compromise. However, a number of terms similar to or slightly different from electrical storm have been used to describe this entity: "Multiple consecutive, appropriate high-energy discharges,"[5] "arrhythmic storm,"[6] "VT clusters,"[7] "electrical instability,"[8] "short-term recurrent VT,"[9] and "incessant VT."[10] Most of these characterizations have been defined and used differently. For example, "incessant VT" has been equated with electrical storm[10,11] or used explicitly in terms of "≥three VT episodes separated by less than 5 minutes."[12] Similarly, "VT clusters" have been defined as electrical storm,[15] in the setting of "≥3 VTs resulting in ICD therapy in a short period of time" (not further specified),[7] or "≥3 adequate ICD interventions within 2 weeks."[16] Villacastin et al. defined electrical storm in ICD recipients as "multiple (≥2) consecutive appropriate shock therapies for a single VT episode."[5] This differs significantly from the current concept of electrical storm and may reflect a high defibrillation threshold.

The definition "≥3 shocks for tachyarrhythmia" used in the era of ICDs without stored electrograms is not useful because it included inappropriate shocks for supraventricular

tachyarrhythmia or sensing artifacts. Likewise, the definition "≥3 appropriate shocks for VT" used for electrical storm does not take into account the influence of (improved) device programming and excludes patients where VTs are terminated by antitachycardia pacing. Today, most workers use the definition proposed by Credner et al. of "≥3 appropriate VT therapies (antitachycardia pacing or shocks) in 24 hour."[18] It may be argued that "≥ 3VT detections within 24 hour which result in ICD therapy (antitachycardia pacing or shocks) or are sustained (>30 second)" may be more appropriate to take into account sustained VT in a monitoring zone not followed by therapy.

The termination of electrical storm has only been defined in one study by Greene et al.[19] in terms of a period of ≥2 weeks without VT recurrence, which seems long and thus highly arguable.

In summary, electrical storm in ICD patients is best defined as the detection of ≥3 VTs in 24 hour. All appropriately detected VTs (treated by ATP, ≥1 shock or eventually untreated in a VT monitoring zone but sustained, that is >30 second according to device memory) form part of the definition. The number of shock discharges and inappropriate detections are irrelevant for the definition. VT episodes in electrical storm have to be separate, that is VT after unsuccessful therapy cannot be regarded as a second episode. In contrast, incessant VT, that is VT starting shortly (after ≥1 sinus cycle and within 5 minutes) after a technically successful therapy should be included in the definition, representing a serious form of electrical storm. Repetitive VTs in the first week after ICD implantation should not be considered as electrical storm (see below).

Incidence of ES in Patients with an ICD

Given the lack of consensus about the definition of electrical storm, it is not surprising that its incidence has been reported to vary significantly from 10% to 60% in ICD patients (Table 1). By considering only studies that defined electrical storm as ≥2–3 VT episodes in 24 hour, electrical storm was documented in approximately 10–25% of ICD patients[12,15,16,19,20] during follow-up periods of 12 to 36 months. In patients with an ICD for primary prevention, electrical storm seems to be less frequent than in those with an ICD for secondary prevention (5% vs 28% in).[16]

Table 2. Electrical Storm: Time to First Occurrence and Number of VT Episodes.

Author	Time after ICD Implantation	No. of VT Episodes
Credner[18]	133 ± 135 days	17 ± 17
Exner[12]	9.2 ± 11.5 months	NA
Greene[19]	599 ± 710 days	55 ± 91
Bänsch[15]	NA	19
Verma[23]	814 ± 620 days	5 ± 5 shocks
Stuber[16]	629 ± 646 days	NA
Brigadeau[39]	Median 1417 days	Median 2 (range 1–9)

NA = not available

Wood et al. found that VT events in ICD patients are not randomly distributed over time[7] but were clustered in the majority of patients with ≥3 VT episodes, the interval between VT episodes being less than 1 hour in 78% of the cases. The 50th percentile for the median time between VT detections for individual patients was as short as 26 minutes.[21]

In one of the earliest report on electrical storm in ICD patients from 1998, the disturbance occurred at a mean of 4–5 months after device implantation.[18] More recent reports revealed that electrical storm occurs typically 2–3 years after ICD implantation,[16,23] (Table 2), a finding that may reflect changes of ICD indications and drug treatment. Multiple VT episodes early after epicardial or transvenous ICD implantation most probably originate from myocardial irritation.[8,22] VT episodes in the first week after ICD implantation are therefore not included into the strict definition of electrical storm because their mechanism appears different from electrical storm which typically occurs later ICD implantation.

While the definition of electrical storm as ≥3 VT episodes in 24 hour may include rather benign arrhythmia clusters, the mean number of VT episodes during an electrical storm can be rather high (e.g. 17–19, cf. Table 2). Verma et al. reported a number of shocks during an electrical storm of 5 ± 5,[23] but the study by Greene et al. reported a mean number of 55 VT episodes, defining the end of electrical storm as a VT free interval of at least 2 weeks.[19]

Triggers of Electrical Storm

Most investigations failed to reveal any clear cause for the development of electrical storm in the majority of patients. Credner et al. observed

hypokalemia, acute myocardial infarction, and acute worsening of heart failure as potential triggers of electrical storm in 26% of their patients,[18] Exner et al. found that patients with electrical storm were less likely to have received a revascularization procedure.[12] Similarly, in the SHIELDS trial a precipitating factor was identified only in 13% of patients.[20] In contrast, Greene et al. found a potential cause of electrical storm in 71% of patients: New or worsened heart failure in 15%, adjustment of or noncompliance to antiarrhythmic medication in 20%, (post ICD implantation in 13%), excess alcohol consumption in 8%, context with other illness in 5%, and unusual psychological stress (driver's license suspension, long-distance journey, etc.) in 10%.[19] Similarly, Bänsch et al. found a potential cause of electrical storm in 65% of patients: Heart failure in 31%, diarrhea or hypokalemia in 20%, fever or psychological stress (before operation, travel) in 4%.[15] Other potential causes of electrical storm (e.g., inappropriate shocks, class III proarrhythmia) have not yet been investigated. These disparate data suggest that obvious causes (ischemia, heart failure, hypokalemia) seem to cause less than 20% of events. Psychological stress may be a an important trigger but requires individualized, thorough history taking and documentation (usually not represented in case record forms of multicenter studies); its role as a trigger of electrical storm or a mere coincidence, however, remains a matter of interpretation. The impact of sympathetic activity on electrical storm is corroborated by findings of a decreased baroreflex sensitivity,[18] therapeutic effect of beta-blockers in contrast to antiarrhythmic drugs,[17] and a peak incidence during the morning hours.[9]

Electrical storm seems to have a specific electrophysiological substrate in the majority of patients. In a study of patients with dilated cardiomyopathy, VT inducibility was an independent significant predictor for the development of electrical storm.[15] In all likelihood, the interplay between autonomic nervous system and electrophysiological substrate (which may change over time due to tissue scarring, ischemia, and increased left ventricular dimensions in progressive heart failure) determines the occurrence of electrical storm.

Arrhythmias and ICD Therapies during Electrical Storm

The vast majority of arrhythmic episodes that constitute an electrical storm consist of monomorphic VT (86–97%, Table 3); polymorphic VT and ventricular fibrillation are unusual causes (1–7%, Table 3). These observations favor the concept of

Table 3. Arrhythmias Causing Electrical Storm and Related ICD Therapy

Author	ES Arrhythmias	ES Therapies	ES Hospitalization
Credner[18]	Pts: 64% mVT, 21% VF, 14% mVT+VF	NA	86% of pts
Greene[19]	Eps: 97% mVT, 3% pVT+VF	Eps: 23% only ATP, 77% with shocks	NA
Bänsch[15]	ES: 87% mVT, 8% pVT/VF, 4% different mVT	ES:100% shocks, 42% ≤3 shocks, 58% >3 shocks	78% of ES, 50% for ≤3 shocks, 100% for >3 shocks
Exner[12]	Initial Eps: 86% mVT, 14% VF or VT+VF	Eps: 46% shocks, 28% ATP alone, 27% ATP+shocks	NA
Verma[23]	Pts: 52% mVT, 48% VF	Pts: 100% shocks (median 5, range 2-43)	NA
Stuber[16]	ES: 93% mVT, 7% pVT	ES: 50% ATP alone,19% ATP + shocks, 31% shocks alone	19% of eps
Hohnloser[20]	ES: 91% mVT, 8% mVT+VF, 1% VF	Eps: 70% ATP alone, 23% ATP + shocks, 7% shocks alone	55% of pts (82% of pts in emergency room)
Brigadeau[39]	ES: 90% mVT, 8% VF, 2% pVT	NA	NA
Gatzoulis[40]	NA	ES: 21 ± 33 ATP and 8 ± 4 shocks	29/32 pts (91%)

ATP = antitachycardia pacing; Eps = episodes; ES = electrical storm, mVT = monomorphic ventricular tachycardia; pts = patients; pVT = polymorphic ventricular tachycardia; VF = ventricular fibrillation.

monomorphic VT induction as outlined above as a more important cause of electrical storm than acute ischemia which is more likely to induce ventricular fibrillation or polymorphic VT.

In this respect, Verma et al found a higher proportion of ventricular fibrillation as the cause of electrical storm, most probably because of their inclusion criteria (at least two shocks).[23] Differences in the arrhythmic expression may also be related to the type of patient population. Compared to cardiac arrest/ventricular fibrillation, patients with ventricular tachycardia as their ICD indication are more likely to develop electrical storm exclusively with monomorphic VT.

The interpretation of stored electrograms plays an important role in tachycardia discrimination. Depending on device filters, amplifiers, and compression algorithms, electrogram morphology differs between manufacturers. In some cases, it may be difficult to distinguish ventricular tachycardia from fibrillation based on right ventricular bipolar electrograms during VT. In the absence of a surface ECG, the type of VT may be classified according to its organization into type I (highly organized: monomorphic signals, isoelectric baseline, cycle length > 200 ms), II (intermediate organization), or III (disorganized: broad or irregular signal morphology, loss of clear isoelectrical baseline, minimal cycle length <200 ms,[24]). Monomorphic reentrant VT would be expected to show type I organization while ventricular fibrillation would most likely appear as type II or III electrograms. The availability of a farfield electrogram (distal coil electrode versus can or similar) may be used as an approximation of the surface ECG and can be valuable to distinguish polymorphic VT/fibrillation from monomorphic VT.

In conclusion, electrical storm consists of monomorphic VT in most patients indicating the presence of reentry due to an electrophysiological substrate. The prevalence of ventricular fibrillation is low indicating other triggers such as acute ischemia. However, the definition of ventricular fibrillation based on stored bipolar electrograms has not been standardized.

Clinical and Prognostic Implications of Electrical Storm

The mortality rate of ICD patients is uncertain. Sudden death occurs in approximately 2% of patients,[4] but data from device interrogation is available in a minority of cases. Death due to incessant recurrent VT has also been reported.[4,15] The most important immediate clinical consequence of electrical storm, however, is hospitalization that is required in approximately 80% of patients (Table 3), particularly with shock delivery (100% hospitalization for >3 shocks).[15] Thus, electrical storm reduces quality of life and may induce a state of anxiety that leads to psychological problems.

Some studies but not all have found electrical storm predictive of an impaired prognosis. Credner et al. did not observe an increased mortality in patients with electrical storm compared to other ICD patients.[18] However, this study involved only 14 patients with electrical storm, and mean follow-up was limited to 13 months. Greene et al. observed a slightly higher mortality in patients with electrical storm compared to patients with appropriate ICD therapy and patients without appropriate ICD therapy (mortality 25%, 16%, and 7%, respectively) that did not reach statistic significance.[19] Over a 1-year follow-up period in the SHIELD trial, ICD patients with electrical storm had no higher mortality (2.7%) than ICD patients with isolated VTs (4.3%) or without any VT (2.4%).[20] In contrast, in the AVID trial, Exner et al. found a significantly higher mortality of patients with electrical storm than in the other study patients (relative risk 2.4) with the highest mortality risk in the first 3 months after electrical storm (relative risk 5.4).[12] Of note, only approximately 40% of patients in the AVID trial received beta-blockers compared to 76% in the study by Credner et al. This may explain the varying incidence (10% vs 20%) and different prognostic significance in the reports on electrical storm. Looking exclusively at patients with nonischemic cardiomyopathy (representing 21% of patients in Credner et al. and 20% in Exner et al.) Bänsch et al. found a significantly higher mortality/ transplantation rate during a mean follow-up of 3 years in patients with a history of electrical storm (54% after 2 years) which was even higher if electrical storm was accompanied by cardiac decompensation (88% after 2 years).[15] Similarly, Verma et al. found an increased mortality in patients with electrical storm compared to control ICD patients[23] and like other investigators, found the increase in mortality to be due to progression of heart failure, not arrhythmic death. In contrast to the AVID trial, patients died typically later than 3 months after electrical storm. This raises the question as to whether electrical

storm is an "inciter" of mortality in ICD patients, a contributing factor, or rather an innocent bystander. Multiple shocks can lead to an increase in troponin levels indicating myocardial injury which may lead to acute inflammation and fibrosis.[25,26] Recurrent ventricular fibrillation can cause intracellular calcium elevation which may contribute to progression of left ventricular dysfunction.[27–29] Therefore, electrical storm particularly with multiple shocks and ventricular fibrillation may contribute to the progression of heart failure. On the other hand, the prognostic role of monomorphic and particularly slow VT (harbinger of terminal heart failure?) treated successfully but repetitively by antitachycardia pacing is unknown. Electrical storm in patients with an ICD may represent an event entirely different from patients without an ICD because the time to therapy is much shorter and therefore the risk of hemodynamic impairment much smaller, and because most VT episodes are terminated by antitachycardia pacing instead of external cardioversion.

Treatment and Prevention of Electrical Storm

The key intervention in electrical storm is reduction of the elevated sympathetic tone by beta-blockers,[17] frequently combined with benzodiazepines.[8,19] Treatment with i.v. amiodarone has also been successful[18,19] and azimilide seems promising, at least in prevention of electrical storm[20] while class I antiarrhythmic drugs are usually unsuccessful[15,17,18] or only useful in combination with amiodarone if the latter fails.[30] Magnesium and potassium may be helpful particularly in patients with prolonged QT intervals or hypokalemia. In some patients, overdrive pacing by increasing the lower rate of the ICD may terminate electrical storm, particularly if dual-chamber pacing is available. Heart failure treatment should be intensified carefully, avoiding a significant decrease of potassium levels from diuretics. Antiischemic treatment by revascularization may be useful in some patients but usually requires a stable condition. Radiofrequency ablation holds great promise in the treatment of electrical storm refractory to amiodarone.[31,32] Two randomized studies (SMS study, VTach study) are currently being conducted to assess catheter ablation as prophylaxis for electrical storm in ICD patients with VT.

ICD programming is probably a key issue to prevent electrical storm. Since sympathetic overreactivity is an important trigger, the risk of shock delivery should be minimized. Antitachycardia pacing can successfully terminate a significant percentage of fast VTs.[33] So-called safety features that apply a shock after a programmable time window (usually 30 second) independent from programming of antitachycardia pacing should be prolonged (e. g. to 2–5 min) or disabled. In most patients, the number of VT cycles necessary for detection can be increased from nominal values (usually 20 cycles for VT) to allow spontaneous termination. It remains unknown if treated VTs would have been sustained had VT detection criteria been programmed more stringent (e.g. requiring $\geq$30 consecutive cycles). Data from the DEFINITE trial suggest that many VT episodes do not need to be treated.[34] Similarly, criteria for redetection can carefully be prolonged to reduce the risk of inappropriate detection of (repetitive) nonsustained VT in many patients. Though there are no data on the incidence of electrical storm as a result of inappropriate shocks, the latter needs to be avoided. Finally, the risk of worsening of heart failure is increased by unnecessary right ventricular pacing in ICD patients[35] and may therefore be a trigger of electrical storm preventable by appropriate programming.

Conclusion and Open Questions

The incidence and prognostic significance of electrical storm in ICD patients are not completely clear because different patient populations (primary vs secondary prophylaxis of sudden cardiac death, ischemic versus nonischemic cardiomyopathy, monomorphic VT versus other ICD indications), different definitions of electrical storm, and different follow-up durations have been used. It appears in approximately 25% of patients, typically somewhat late (6–36 month) after ICD implantation. Electrical storm seems to have a low immediate mortality (1%) but frequently (50–80%) leads to hospitalization, particularly after repetitive shocks. Several issues remain to be investigated in treatment, particularly prevention: role of prophylactic antiarrhythmic drug treatment in ICD patients as indicated in three studies with sotalol, amiodarone, and azimilide,[20,36,37] the use of prophylactic catheter ablation, and the role of ICD programming. The latter includes antitachycardia pacing instead of shock therapy whereever

possible, longer detection times to allow spontaneous VT termination, and potentially atrial (!) overdrive, an underlying hypothesis that failed in the DAVID trial due to a high incidence of unnecessary right ventricular pacing in the DDDR mode used in the overdrive group.

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