Electrical Storm

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17-4-2019

INTRODUCTION - DEFINITIONS

- A ***distinct medical emergency*** → multiple episodes of sustained VA within a short time period typically 24 hours.
- In the majority of cases, ***monomorphic VT*** constitutes the primary arrhythmia, however, polymorphic VT and VF are also implicated.
- ***In patients without an ICD*** → ≥3 discrete episodes of VA within 24 hours, or incessant VA for more than 12 hours
- ***In patients with an ICD*** → ≥3 appropriate device therapies within a 24-hour period, separated from one another by at least 5 minutes
- Predominantly afflicts patients with severe structural heart disease, however, this condition is also reported in those with channelopathies such as Brugada and LongQT Syndrome.

Incessant VT is a condition in which a sustained VT resumes within 5 minutes after successful ICD therapy and continues for over 12 hours.

Definition of electrical storm: diversity in the literature

- **Before the ICD era** → ≥2 VT/VF episodes within 24 h
- ≥2 VT/VF requiring ICD shock within 24 h
- ≥2 hemodynamically relevant VT in 24 h'
- ≥4 VT in 1 h
- ≥2 shocks for one VT episode
- ≥3 VT episodes separated by less than 1h of sinus rhythm

INCIDENCE – PREDICTIVE FACTORS

- The overall reported incidence → 10–30% in patients with a secondary prevention ICD → at an average of 4–9 months after ICD implantation
- The incidence is 4–7% in patients with a primary prevention ICD, occurring 18–24 months after ICD implantation

Clinical factors associated with a higher incidence of ES

✓*Lower LVEF*

✓*Implantation of a secondary prevention ICD*

✓*Treatment with class I AADs*

✓*Monomorphic VT as the underlying arrhythmia*

Characteristics and Outcomes in Patients With Electrical Storm

Age (years)	62.0 ± 12.8
Men	86.1%
Ischemic etiology	72.2%
Secondary prevention	9.9%
NYHA class of heart failure at admission	
II	60%
III	26.3%
IV	13.8%
Infection at admission	14.3%
Acute coronary syndromes	4.0%
Arterial hypertension	59.4%
Stable coronary artery disease	52.0%
Previous myocardial infarction	60.4%
Previous PCI	52.4%
Previous CABG	14.5%
History of stroke and/or transient ischemic attack	7.1%
Atrial fibrillation or flutter	45.5%
Diabetes mellitus	34.7%
Hyperlipidemia	39.2%
Chronic kidney disease (class ≤3)	20.8%
Chronic obstructive pulmonary disease	9.9%
History of hyperthyroidism	11.9%
History of hypothyroidism	9.3%
Current smoking	9.4%
Type of cardiac implantable electronic device	
Single chamber ICD	23.3%
Dual chamber ICD	28.9%
CRT-D	47.8 %
No device	10.9%
White blood cells (10^6/ul)	9.2 ± 3.9
Red blood cells (10^6/ul)	4.5 ± 0.6
NT pro-BNP (pg/ml)	3017 ± 2345
Potassium (mmol/L)	4.18 ± 0.65
Thyroid stimulating hormone (mU/L)	1.95 ± 2.18

Baseline echocardiographic and electrocardiographic parameters

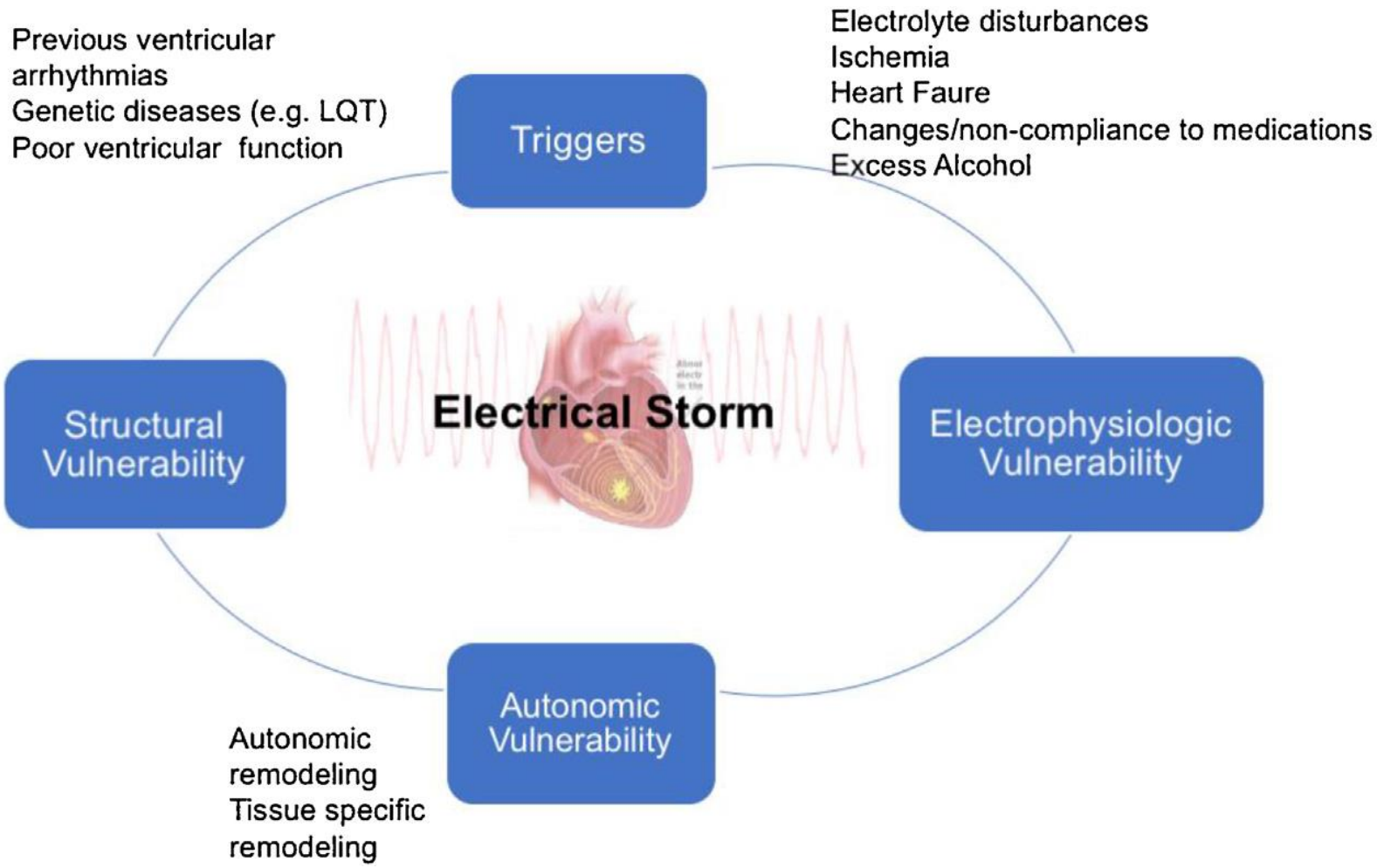
Variable	n = 101
Left ventricle ejection fraction, (IR)	26.0% (12–46)
Patients with left ventricle ejection fraction <35	61.9%
Left ventricle end-diastolic volume, ml (IR)	220 (98–530)
Left ventricle end-systolic volume, ml (IR)	163 (55–440)
Severe mitral regurgitation	11.3%
Severe tricuspid regurgitation	6.2%
Severe aortic stenosis	1.01%
QRS complex duration, ms	135 ± 53
QT corrected interval duration, ms	456.6 ± 51.9

Gadula-Gacek et al 2019 Am J Cardiol

Mechanisms underlying electrical storm

- ✓ An interplay between the autonomic nervous system, cellular milieu and a predisposing electrophysiological substrate
- ✓ Trigger and the substrate may change over time influenced by the progression of scarring, left ventricular remodelling and the progression of heart failure.

Mechanisms underlying electrical storm



Geraghty et al 2019 Heart, Lung, Circulation

Electrical storm: disease or symptom

- ✓ Electrical storm directly affects the patients' prognosis → BUT by preventing the next episode of electrical storm the mortality does not necessarily decrease
- ✓ Electrical storm often represents part of the natural history of advanced cardiac disease and may predict a serious deterioration in the underlying processes.

Electrical storm: Prognostic implications

- ✓ Increased mortality rate of up to 14% in the first 48 hours from presentation
- ✓ AVID (AAD vs ICD) study → secondary prevention ICDs, a 5.6-fold increase in mortality in the first 12 weeks subsequent to the development of ES
- ✓ MADIT II → associated with a 18-fold increase risk of death in the first 3 months after the event
- ✓ Recurrent storm may occur in 50–81% of patients over the subsequent year

Characteristics and Outcomes in Patients With Electrical Storm

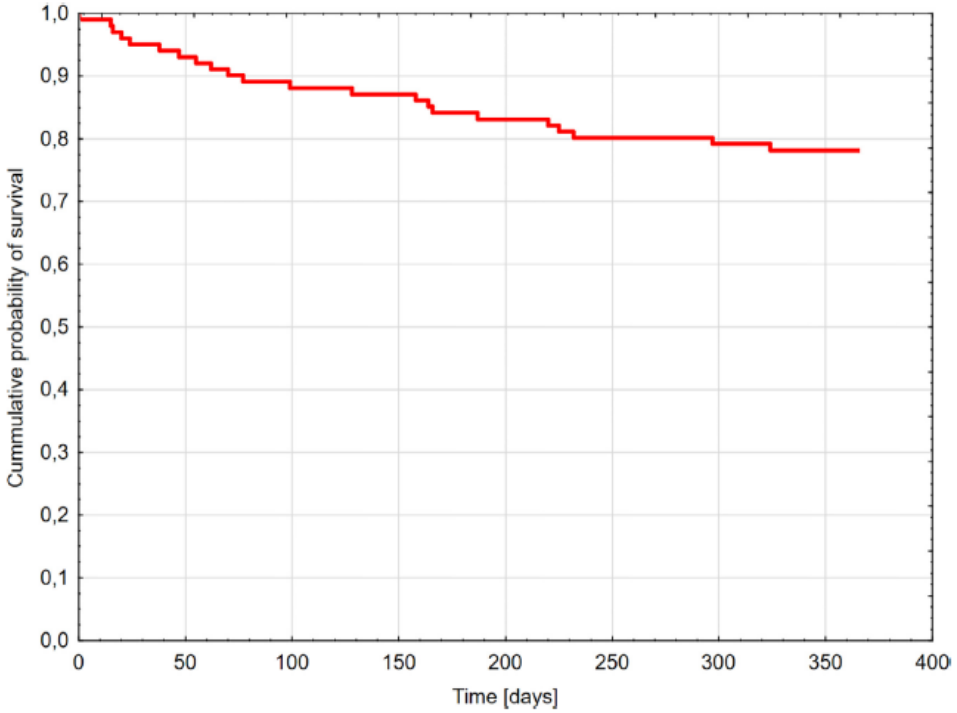


Figure 2. All-cause mortality in the population of patients with electrical storm.

Predictors of 12-month mortality in the study population (Cox proportional hazards model results)

NYHA III or IV on admission	8.53	1.12–16.83	0.03
Creatinine level (per 1 umol/L more)	1.02	1.004–1.04	0.02
NT pro-BNP (per pg/ml)	1.01	1.001–1.05	0.03
Hemoglobin (per 1 mmol/L less)	0.36	0.15–0.87	0.02

Gadula-Gacek et al 2019 Am J Cardiol

Role of electrical storm as a mortality and morbidity risk factor and its clinical predictors: a meta-analysis

Guerra et al. 2013 Europace

Study or subgroup	Electrical storm Events	Total	No Electrical storm Events	Total	Weight	Risk ratio Random, 95% CI
Fries *et al.* 1997	9	34	3	57	11.0%	5.03 [1.46, 17.31]
Credner *et al.* 1998	2	14	3	43	7.9%	2.05 [0.38, 11.04]
Greene *et al.* 2000	10	40	9	57	15.0%	1.58 [0.71, 3.54]
Exner *et al.* 2001	34	90	28	184	18.6%	2.48 [1.61, 3.82]
Hohnloser *et al.* 2006	4	148	10	235	11.8%	0.64 [0.20, 1.99]
Sesselberg *et al.* 2007	15	27	41	142	18.6%	1.92 [1.26, 2.94]
Nordback *et al.* 2010	13	40	24	684	17.1%	9.26 [5.11, 16.79]
Total (95% CI)		**393**		**1402**	**100.0%**	**2.51 [1.38, 4.58]**
Total events	87		118			

Heterogeneity: $\tau^2 = 0.46$; $\chi^2 = 28.59$, df = 6 ($P < 0.0001$); $I^2 = 79\%$

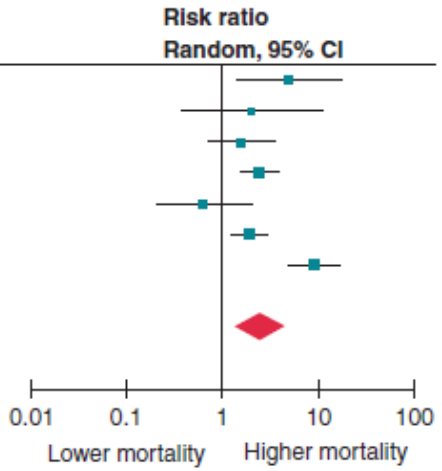


Figure 3 Effect of ES on all-cause mortality when compared with positive previous history of VT/VF but no ES. CI, confidence interval; df, degrees of freedom.

Study or subgroup	Electrical storm Events	Total	No Electrical storm Events	Total	Weight	Risk ratio Random, 95% CI
Fries *et al.* 1997	9	34	2	62	12.7%	8.21 [1.88, 35.83]
Credner *et al.* 1998	2	14	3	79	11.1%	3.76 [0.69, 20.52]
Greene *et al.* 2000	10	40	9	125	18.3%	3.47 [1.52, 7.94]
Exner *et al.* 2001	34	90	41	183	21.9%	1.69 [1.16, 2.46]
Hohnloser *et al.* 2006	4	148	6	250	14.5%	1.13 [0.32, 3.93]
Sesselberg *et al.* 2007	15	27	41	550	21.4%	7.45 [4.76, 11.66]
Total (95% CI)		**353**		**1249**	**100.0%**	**3.34 [1.52, 7.31]**
Total events	74		102			

Heterogeneity: $\tau^2 = 0.69$; $\chi^2 = 30.97$, df = 5 ($P < 0.00001$); $I^2 = 84\%$

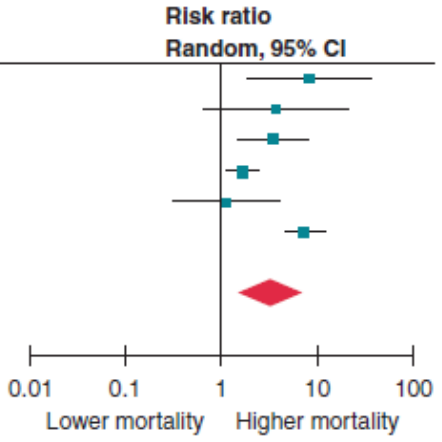
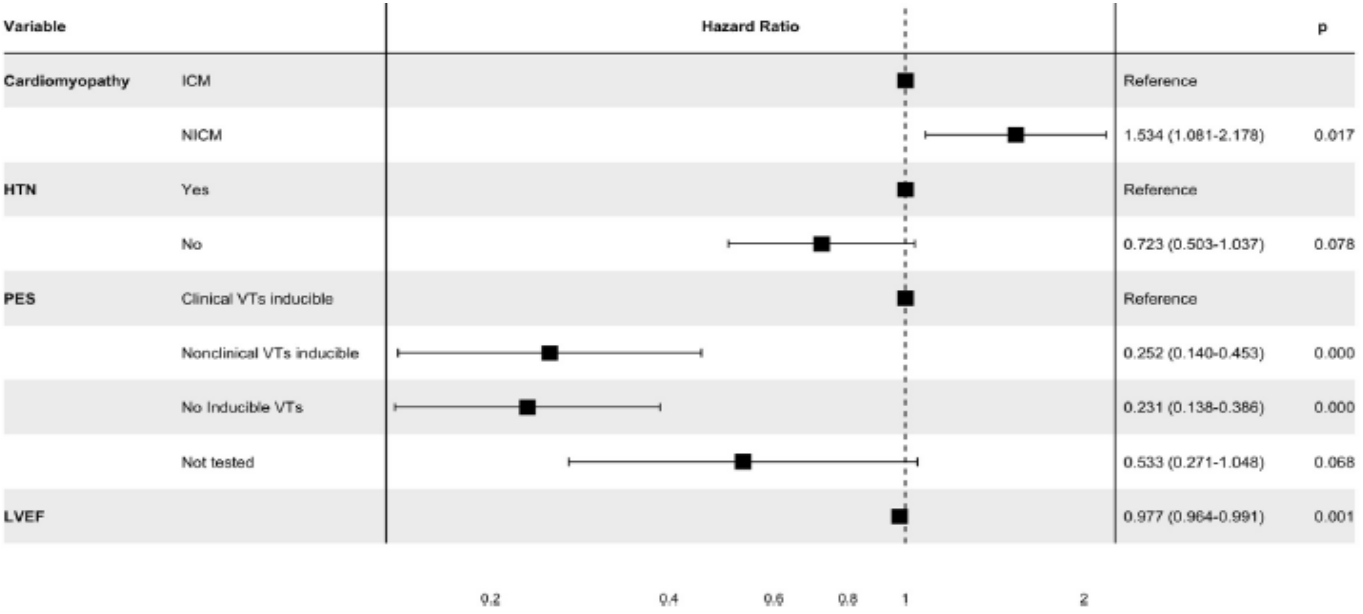


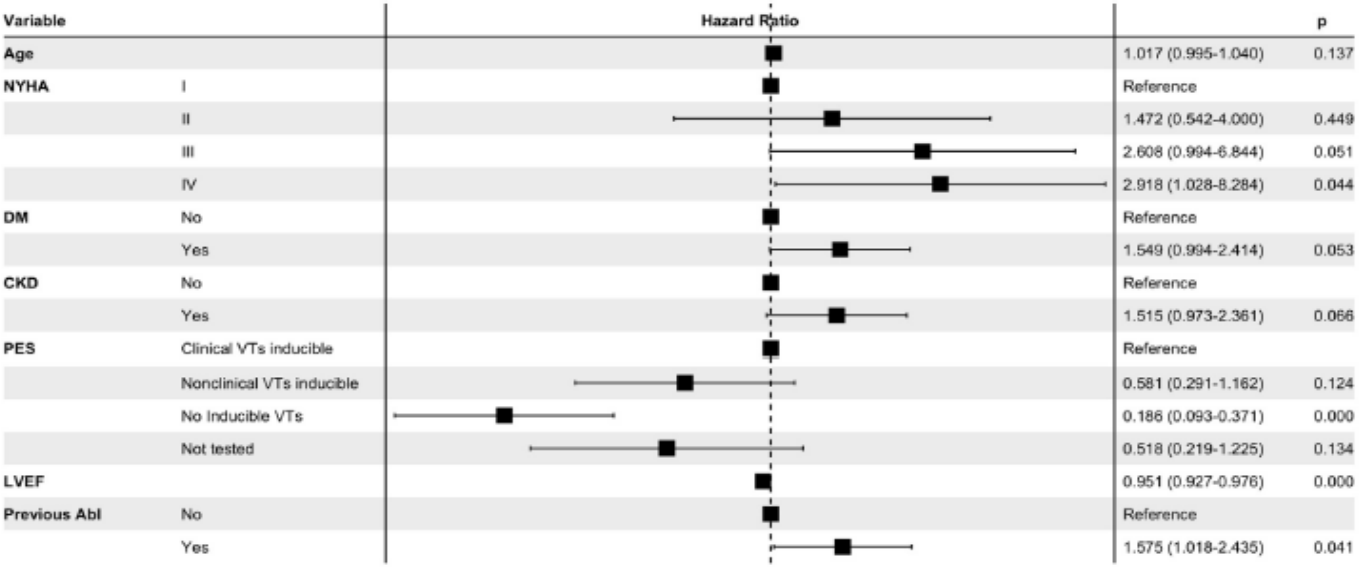
Figure 4 Effect of ES on all-cause mortality when compared with no history of previous VT/VF. CI, confidence interval; df, degrees of freedom.

Prognosticators in Electrical storm patients

Recurrent VT



Mortality



Vergara et al 2017 Heart Rhythm

MANAGEMENT OF ELECTRICAL STORM

- Electrical storm is a clinical emergency
- Triggering causes or exacerbating factors should be sought, including a systematic search for ischemia, decompensation of heart failure, changes to medications, bradycardia-induced tachyarrhythmias, or other systemic illness.
- 10–25% of patients may have reversible factors triggering the electrical storm episode

- ✓ Management guidelines for VA storms rely on anecdotal evidence because there are multiple potential underlying mechanisms.
- ✓ To date, no randomised trials have been conducted in this group of patients.

MANAGEMENT OF ELECTRICAL STORM

Several therapeutic modalities have been proposed

- *Device reprogramming*
- *Pharmacotherapy*
- *Sedation*
- *Neuro-axial modulation*
- *Radiofrequency catheter ablation*

Radiofrequency catheter ablation is emerging as the standard-of-care in patients with electrical storm refractory to optimal medical management.

Treatment of electrical storm: mechanism and trigger

Searching for and correction of reversible factors

- In the majority of cases, no clear cause for electrical storm can be identified.
- Triggers → electrolyte imbalance, acute ischaemia, exacerbation of heart failure, adjustment of or non-compliance to anti-arrhythmic medication and recent introduction to biventricular pacing
- Flow limiting CAD and volume overload should be adequately treated → Decreased LV wall stress can be achieved with non-invasive and invasive haemodynamic support (LVAD, ECMO etc)
- Fever is a more rare trigger of electrical storm, and is especially important in patients with Brugada syndrome

Treatment of electrical storm: mechanism and trigger

Searching for and correction of reversible factors

Table 1 **Triggers of electrical storm**

Commonly reported
Acquired conditions
Acute MI and ischemia
CHF decompensation
Electrolytye abnormalities (Hypokalemia, Hypomagnesemia)
Hyperthyroidism
Antiarrhythmic drug therapy (Vaughan-Williams Class IA, Class III)
Genetic
Long QT syndromes
Brugada syndrome
Catecholaminergic polymorphic ventricular tachycardia
Uncommon but reported causes of electrical storm:
Implantation of a right vagal stimulator [131]
Pneumococcal meningitis[132]
J-point elevation[133]
Pantoprazole[63]
RV pacing[134]
CRT device[51, 52]
SIRS from community acquired pneumonia[135]
Stress cardiomyopathy [136]

Treatment of electrical storm: mechanism and trigger

Device programming

- ✓ Shocks delivered for self-limiting haemodynamically tolerable arrhythmias ought to be avoided.
- ✓ Detection time can be prolonged and ATP can be given as an initial therapy Augmentation of ATP attempts, when feasible, is encouraged especially when shown previously to be successful
- ✓ During an electrical storm an effort should be made to avoid further conscious shocks, and temporary disabling of shock therapy may be considered.

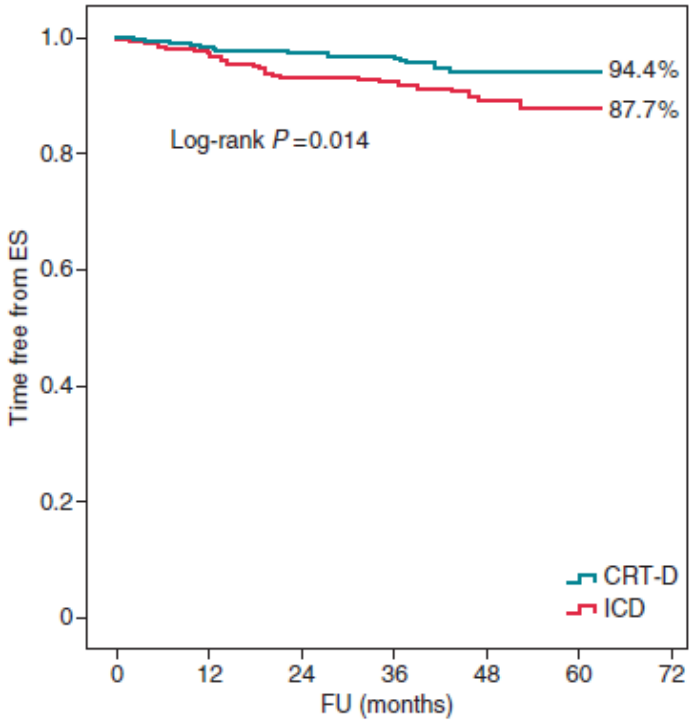
Predicting electrical storms by remote monitoring of implantable cardioverter-defibrillator patients using machine learning

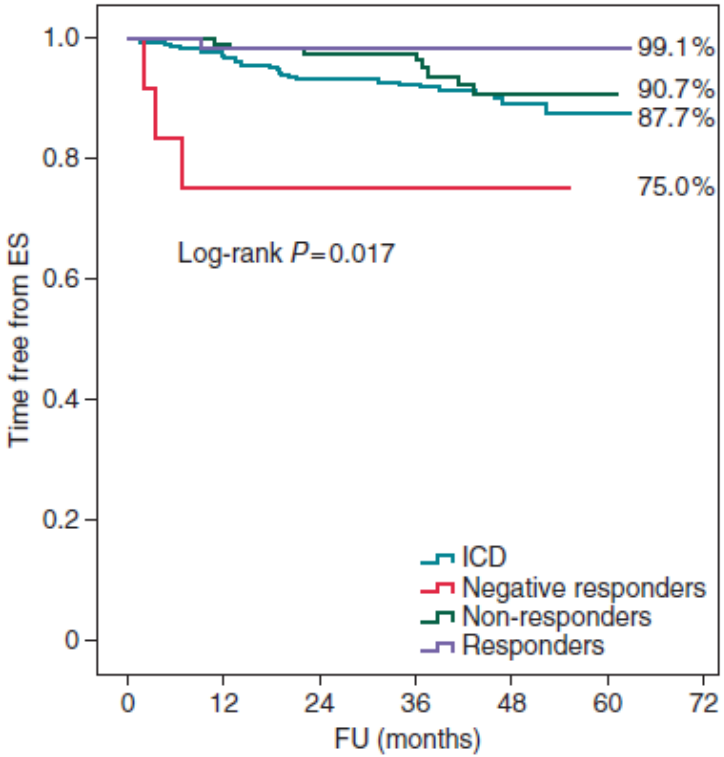
Variables	Description
OneOrMoreShocksPerDay	Indicates the occurrence of one or more ventricular high-voltage shocks during the day
VtVfEpisodes	Number of VT and VF episodes during the day
VRateDuringVtVf	Ventricular rate during VT and VF episodes
VRateDuringAtAf	Ventricular rate during atrial tachycardia and fibrillation (AT and AF) episodes
NSTEpisodes	Number of non-sustained (non-treated) tachycardia events during the day (i.e. tachycardia events that did not lead to an ATP or shock treatment)
VPercentPacingPerDay	Percentage of ventricular pacing during the day
AvgVRateDay	Average ventricular heart rate during the day (08:00 a.m.–08:00 p.m.)
AvgVRateNight	Average ventricular heart rate during the night (12:00 p.m.–04:00 a.m.)
ActivityPerDay	Activity measure during the day
Model	Type of device (conventional or biventricular ICD)

	Logistic regression	Random forest
Accuracy	0.96	0.96
AUC	0.75	0.80

Shakibfar et al. 2018 Europace

Cardiac resynchronization therapy and electrical storm: results of the OBSERVational registry on long-term outcome of ICD patients (OBSERVO-ICD)





Patients with CRT had a lower incidence of ES when compared with propensity-matched ICD patients. The long-term benefit of CRT seems to be due to the improved haemodynamics, as CRT-responders performed markedly better over a long-term follow-up.

Guerra et al. 2017 Europace

Immediate electrical storm of Torsades de Pointes after CRT-D implantation in an ischemic cardiomyopathy patient

Cardiac Resynchronization Therapy and its Potential Proarrhythmic Effect

Electrical Storm Induced by Cardiac Resynchronization Therapy Is Determined by Pacing on Epicardial Scar and Can be Successfully Managed by Catheter Ablation

Pacing in proximity to scar during cardiac resynchronization therapy increases local dispersion of repolarization and susceptibility to ventricular arrhythmogenesis.

Electrical storm of monomorphic ventricular tachycardia after a cardiac-resynchronization-therapy-defibrillator upgrade

Ventricular Tachycardia Storm After Initiation of Biventricular Pacing: Incidence, Clinical Characteristics, Management, and Outcome

- occurred in 4% patients
- characterized by recurrent sustained monomorphic VT
- all patients were men
- 85% ischemic heart disease
- developed a mean of 16 ± 12.5 days after initiation of BVP
- refractory to intravenous antiarrhythmic medication

Patient	Management	Antiarrhythmic Medication on Discharge	Outcome
1	RFA	Amiodarone	OHT that hospitalization
2	Turn off LV pacing	Quinidine	Progressive CHF and death in 5 months
3	RFA	Amiodarone	Progressive CHF and death in 1 month
4	RFA	Amiodarone	Progressive CHF and death in 3 months
5	Lower LV lead output	Amiodarone	Progressive CHF on home milrinone
6	Turn off LV pacing	Amiodarone	Listed for OHT (status 1B)
7	Turn off LV pacing, then RFA	Amiodarone	Recurrent CHF hospitalizations requiring inotropic therapy
8	Turn off LV pacing then switch to 2nd epicardial LV lead	Quinidine	Recurrent CHF hospitalizations requiring inotropic therapy, recurrent MMVT

Nayak et al 2008 J Cardiovasc Electrophysiol

Treatment of electrical storm: mechanism and trigger

- ***Anti-arrhythmic drugs***

- First step is the administration of beta-blockers → blocking the sympathetic system → Adding beta-blockers intravenously in electrical storm patients already on oral beta-blocker therapy may help to keep an electrical storm episode under control
- Propranolol → demonstrated to be effective in suppressing VAs as compared to metoprolol and amiodarone
- In the presence of structural heart disease → amiodarone is one of the most frequently used drugs for the treatment of electrical storm.
- Procainamide → superiority compared to amiodarone for the treatment of haemodynamically tolerated monomorphic VT → only in patients without manifest heart failure and without severely depressed LVEF

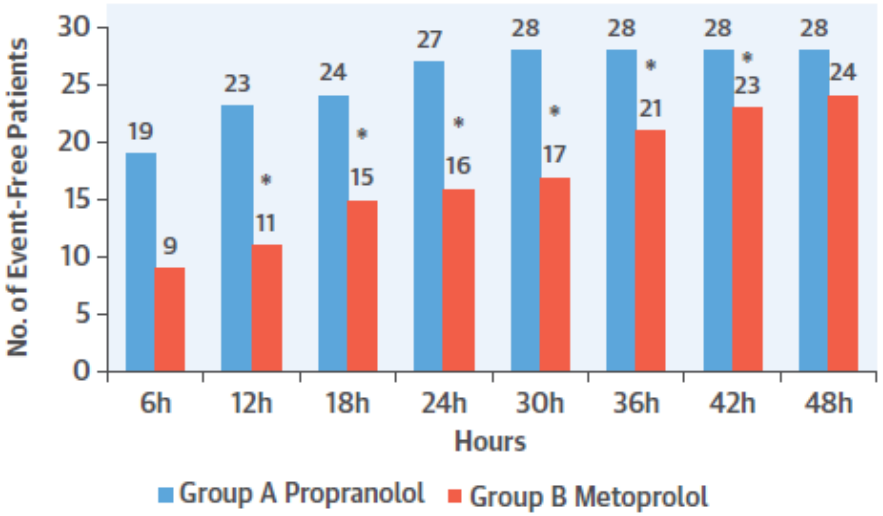
Treatment of electrical storm: mechanism and trigger

Anti-arrhythmic drugs

- The incidence of IV-amiodarone-refractory electrical storm is appx 30%.
- IV-amiodarone-refractory VT storms are frequently induced by triggering premature ventricular contractions (PVCs) and may be successfully suppressed with additional administration of mexiletine
- Lidocaine → used in the setting of acute ischaemia
- Drug combinations are sometimes necessary to alter electrical instability.
- AADs carry the risk of decreasing the cycle length of re-entry VAs and make VT more stable, which may precipitate to incessant VT.

Propranolol Versus Metoprolol for Treatment of Electrical Storm in Patients With Implantable Cardioverter-Defibrillator

METHODS Between 2011 and 2016, 60 ICD patients (45 men, mean age 65.0 ± 8.5 years) with ES developed within 24 h from admission were randomly assigned to therapy with either propranolol (160 mg/24 h, Group A) or metoprolol (200 mg/24 h, Group B), combined with IV amiodarone for 48 h.



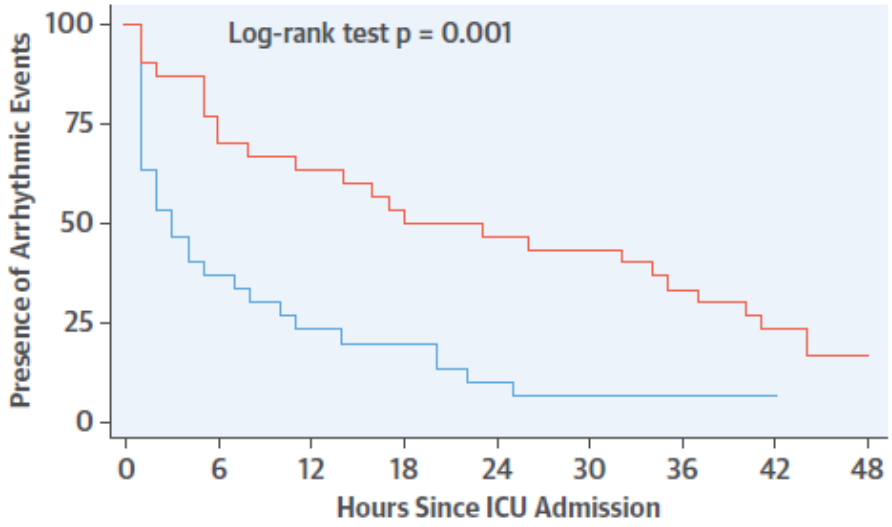


TABLE 3 Multivariable Cox Proportional Hazards Model Examining the Effect of Therapy After Controlling for Patient Baseline Characteristics

	HR	95% CI	p Value
Type of therapy			
Group B	Reference	–	–
Group A	0.225	0.112-0.453	<0.001

Chatzidou et al 2018 JACC

Treatment of electrical storm: mechanism and trigger

Overdrive pacing and sedation

- Temporary (atrial) overdrive pacing may help to interrupt an incessant or re-occurring VA, especially in conditions such as Brugada and early repolarisation syndrome
- Overdrive pacing helps by preventing PVCs from occurring and reduces early after-depolarisation
- As the sympathetic nervous system plays a major role in the initiation but also the maintenance of VAs, sedation and/or intubation may be needed in order to suppress the sympathetic tone.
- A complete sympathetic blockade can be performed by left cardiac sympathetic denervation

Treatment of electrical storm: mechanism and trigger

- ***Radiofrequency catheter ablation***
- In the majority of electrical storm patients the episodes are characterised by a monomorphic VT based on re-entry → Therefore catheter ablation is an important treatment option for electrical storm
- There is also a role for catheter ablation in patients who suffer from recurrent VF episodes.
- Compared to medical therapy catheter ablation reduces the number of subsequent VT episodes especially when VT ablation is performed within one month of electrical storm.
- VT ablation in patients with a LVEF of 25% or greater is shown most beneficial.
- In a first time electrical storm population, VT ablation was significantly more effective than any other form of therapy in reducing death at any time, even though the recurrence rate was not lower in the catheter ablation group.
- Importance of the selection of patients as potential candidates for ablation.

Radiofrequency catheter ablation

Chronic IHD

Urgent catheter ablation is recommended in patients with scar-related heart disease presenting with incessant VT or electrical storm.	I	B
Catheter ablation is recommended in patients with ischaemic heart disease and recurrent ICD shocks due to sustained VT.	I	B

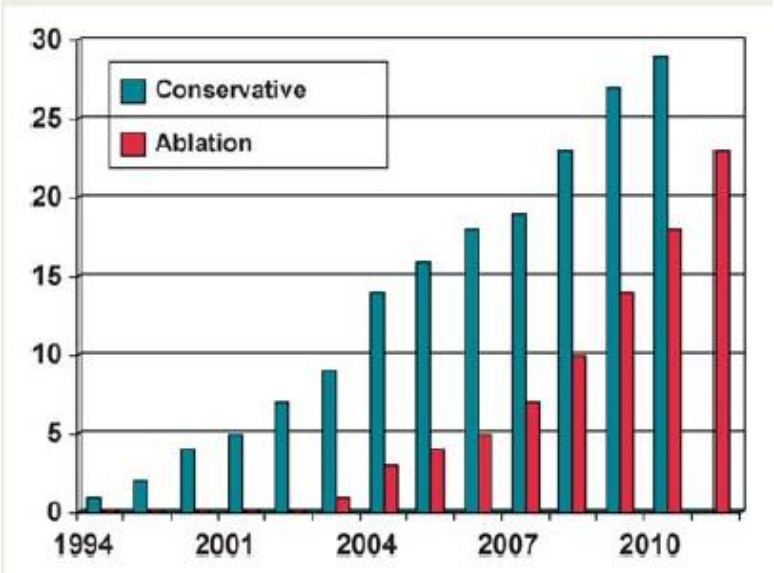
ACS

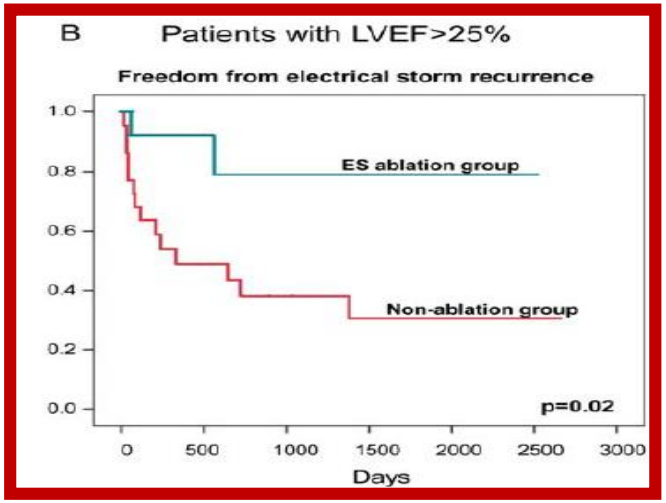
Radiofrequency catheter ablation at a specialized ablation centre followed by the implantation of an ICD should be considered in patients with recurrent VT, VF or electrical storms despite complete revascularization and optimal medical treatment.	IIa	C

Brugada

Catheter ablation may be considered in patients with a history of electrical storms or repeated appropriate ICD shocks.	IIb	C

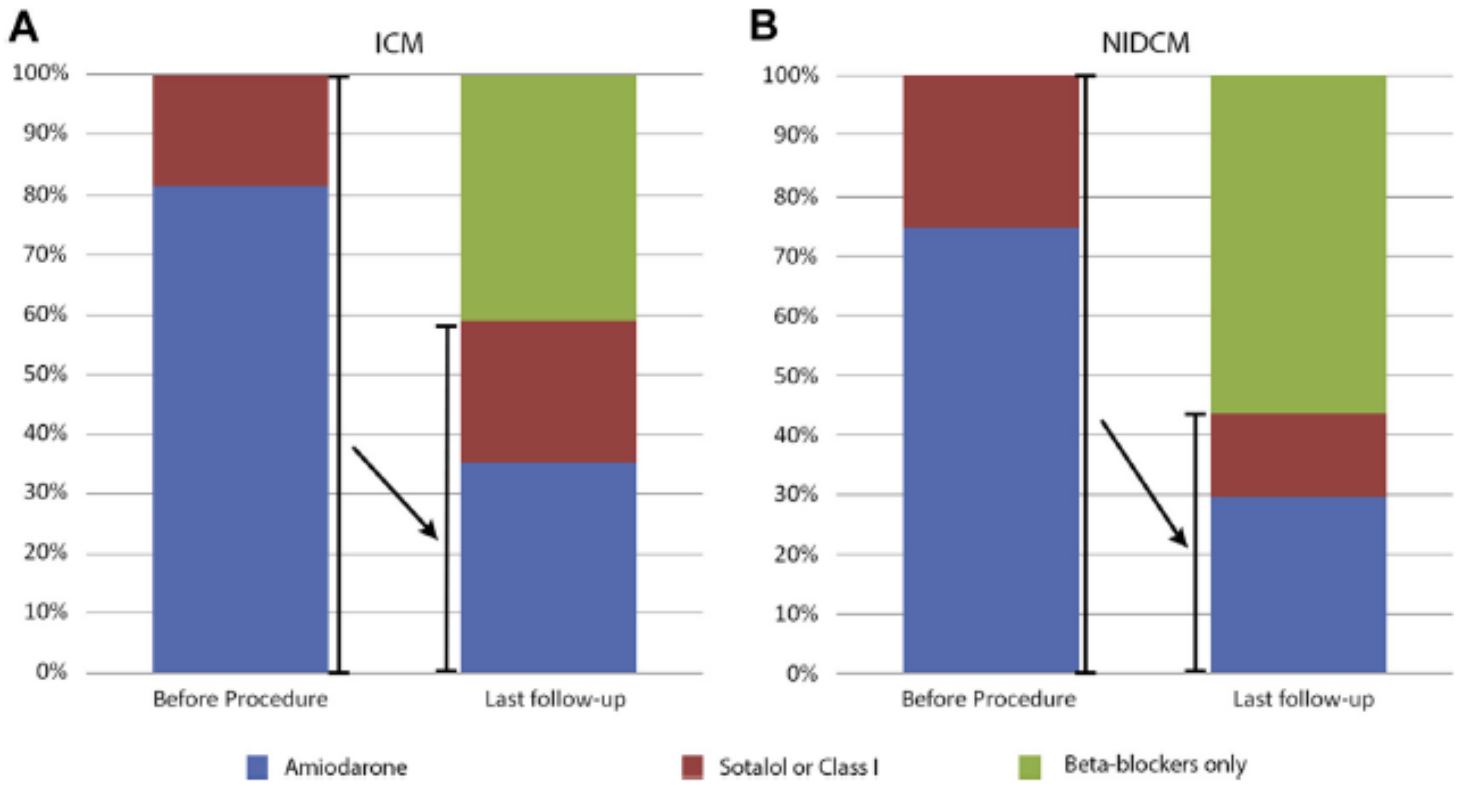
Ablation or conservative management of electrical storm due to monomorphic ventricular tachycardia: differences in outcome





Izquierdo et al 2012 Europace

Long-Term Outcomes of Catheter Ablation of Electrical Storm in Nonischemic Dilated Cardiomyopathy Compared With Ischemic Cardiomyopathy

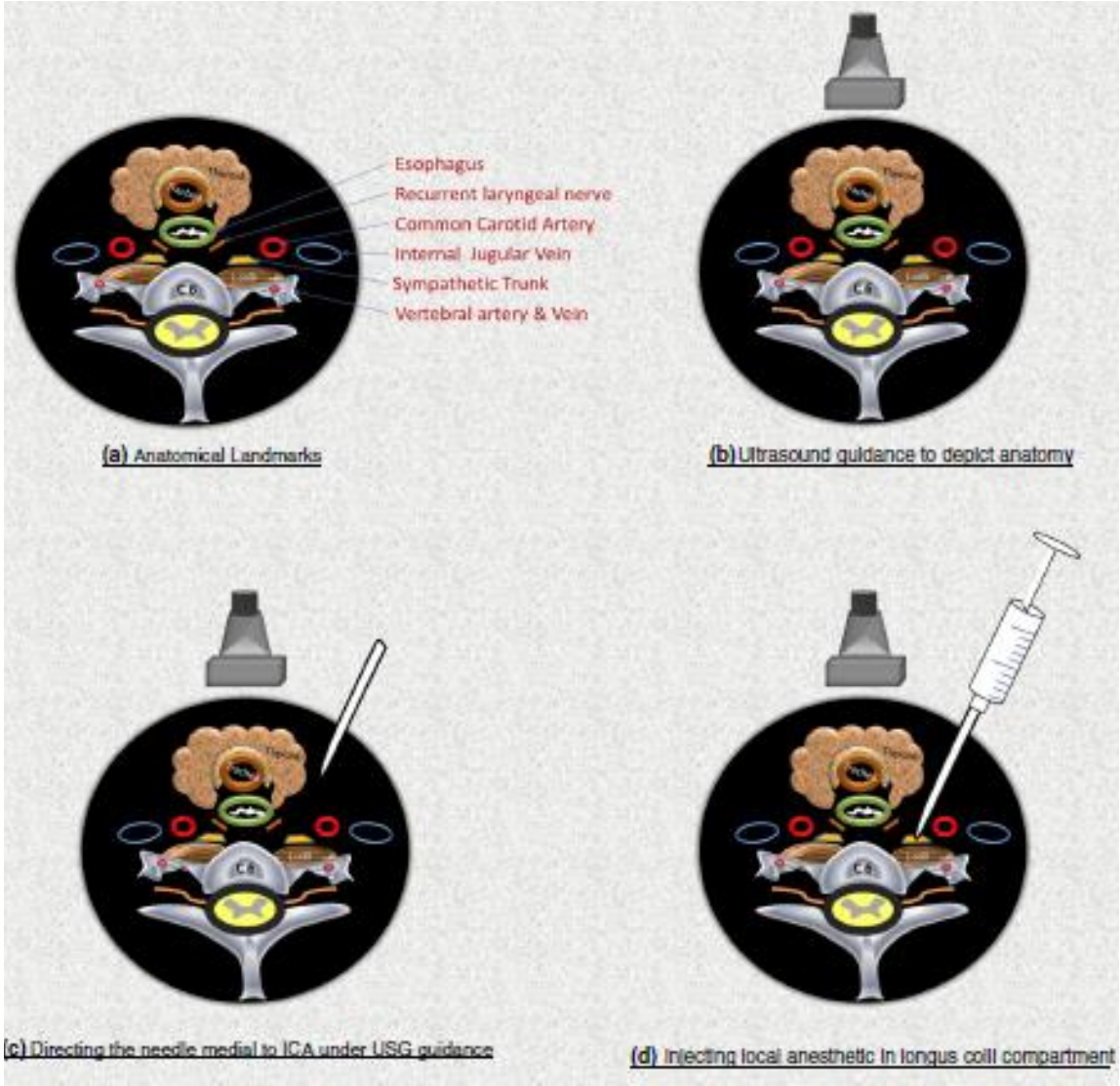


Muser et al 2017 JACC Clin Electrophysiol

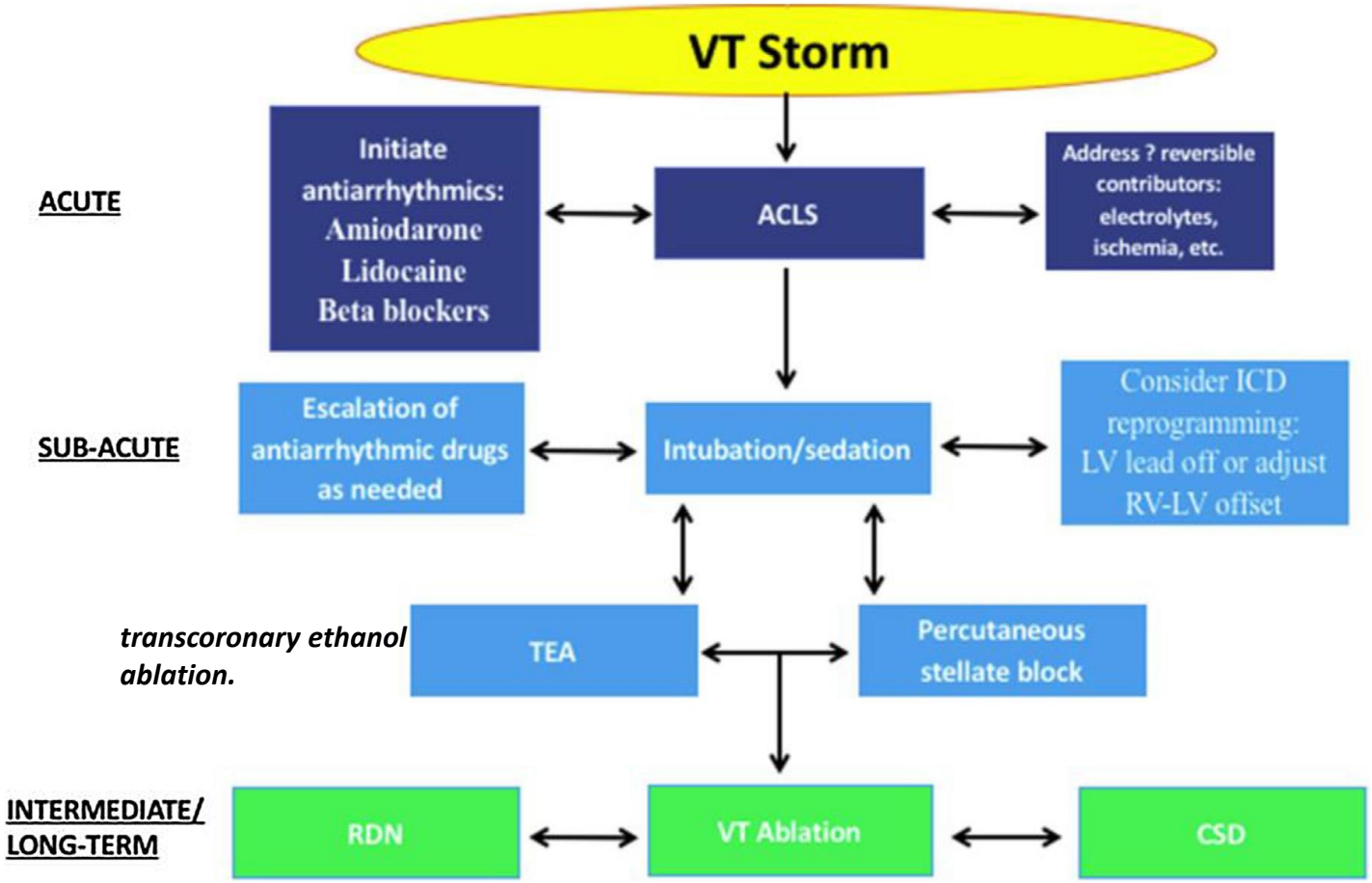
Treatment of electrical storm: mechanism and trigger

➢ Neuraxial Modulation

- Thoracic ***epidural anaesthesia*** involves percutaneous administration of local anaesthetic into the thoracic epidural space → ***Temporary***
- ***Stellate ganglion blockade*** involves percutaneous injection of local anaesthetic into the left or both stellate ganglia, reducing sympathetic outflow to the heart via blockade of afferent and efferent neurons → ***Temporary***
- ***Cardiac sympathetic denervation*** surgically removes the lower half of the left or bilateral stellate ganglia and the T2–T4 thoracic ganglia → ***Permanent***
- ***Renal sympathetic denervation*** involves catheter ablation of the neural plexus in and around the renal artery adventitia – ***Novel approach !!!***

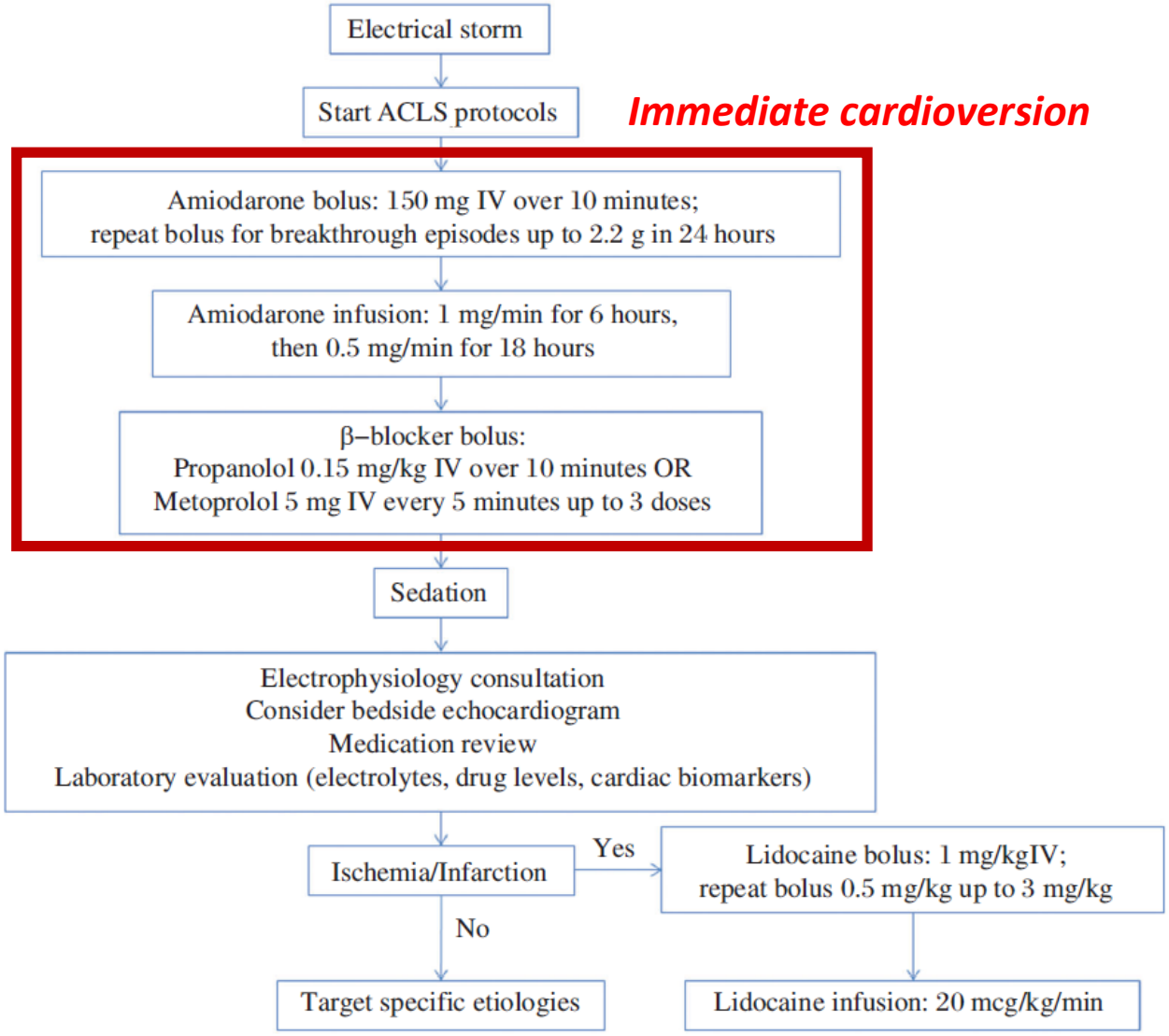

Esophagus
Recurrent laryngeal nerve
Common Carotid Artery
Internal Jugular Vein
Sympathetic Trunk
Vertebral artery & Vein
(a) Anatomical Landmarks
(b) Ultrasound guidance to depict anatomy
(c) Directing the needle medial to ICA under USG guidance
(d) Injecting local anesthetic in longus colli compartment

Interventions followed for the treatment of ES in the immediate, sub-acute and long term management

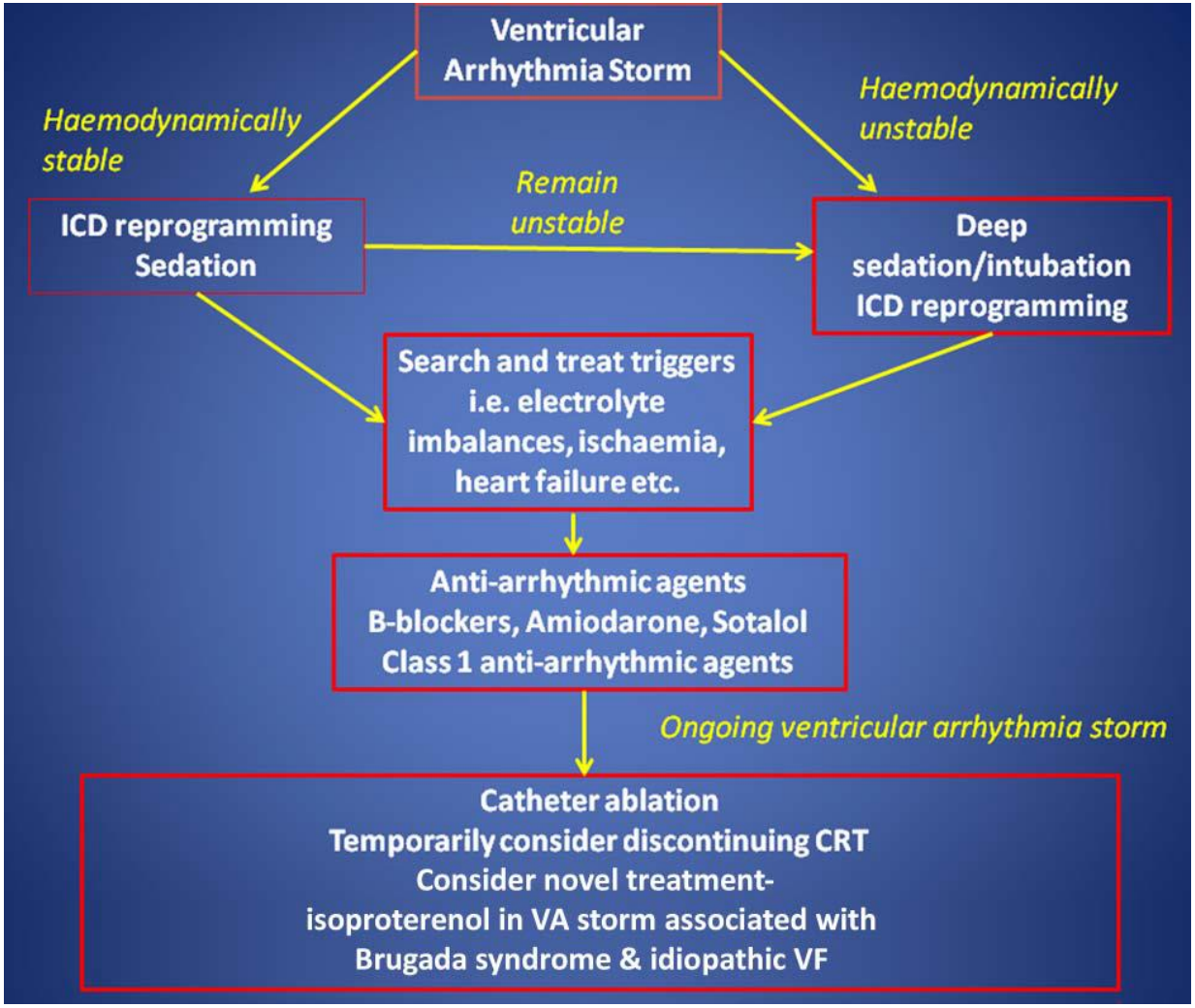


Bradfield et al 2018 Heart Rhythm

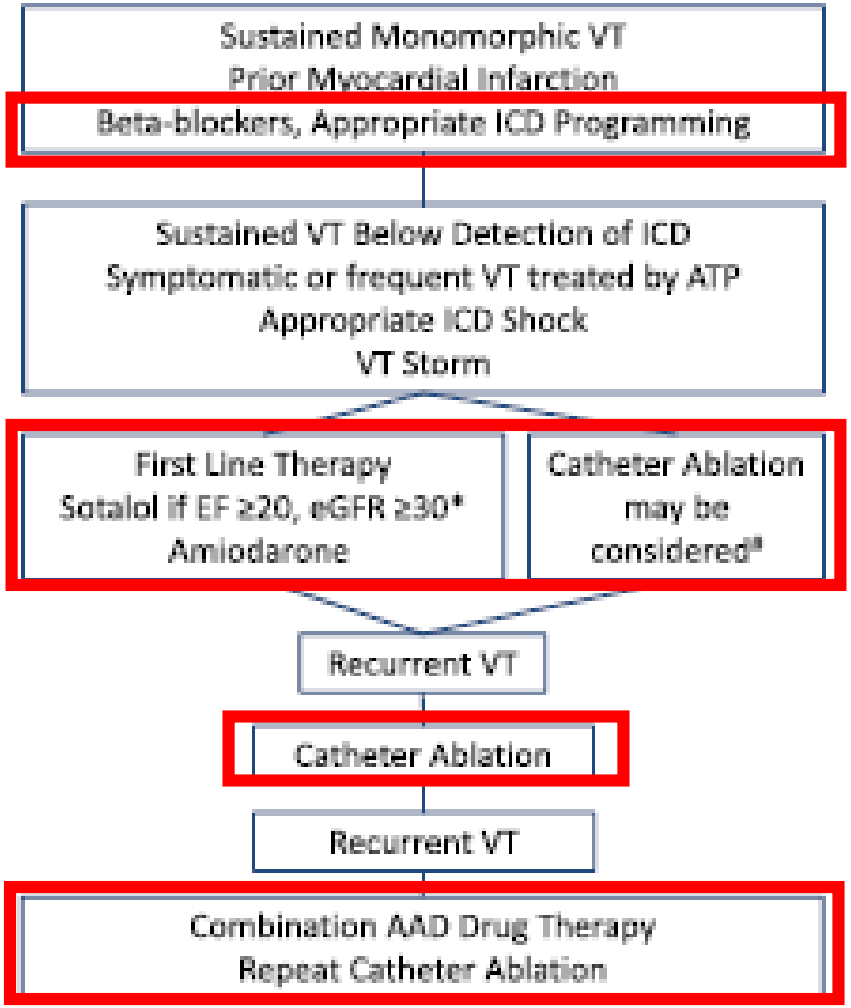
Interventions followed for the treatment of ES



Interventions followed for the treatment of ES in ICD patients



Ventricular Tachycardia with ICD Shocks: When to Medicate and When to Ablate



AbdelWabab et al 2017 Curr Cardiol Rep

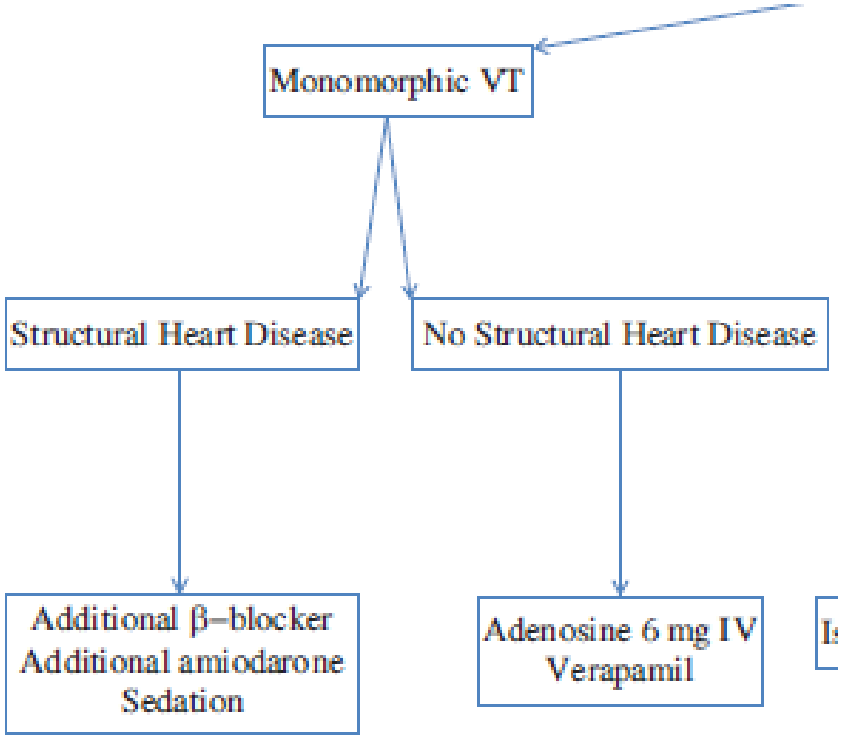
Anti-arrhythmic medications and treatment for acute management of electrical storm

Treatments
Amiodarone
Bolus: 150 mg IV over 10 minutes, can repeat up to total 2.2 g in 24 hours
Continuous infusion: 1 mg/min for 6 hours, then 0.5 mg/minute for 18 hours
β-blockers
Metoprolol bolus: 5 mg IV every 5 minutes up to 3 doses in 15 minutes
Propranolol bolus: 0.15 mg/kg IV over 10 minutes, then 3 to 5 mg IV every 6 hours to maintain sinus rhythm, unless heart rate is below 45 bpm
Esmolol bolus: 300 to 500 mg/kg IV for 1 minute
Esmolol infusion: 25 to 50 mg/kg/min and can titrate upward at 5 to 10 minute intervals until a maximum dose of 250 mg/kg/min is reached
Class I agents
Quinidine: 1000 mg by mouth daily (for Brugada syndrome)
Lidocaine bolus, pulseless VT/VF: 1.0 to 1.5 mg/kg IV, repeat dose of 0.5–0.75 mg/kg IV up to a total dose of 3 mg/kg (for ischemia/infarction)
Lidocaine bolus, non-pulseless VT/VF: 0.5–0.75 mg/kg IV, repeat dose of 0.5–0.75 mg/kg IV up to a total dose of 3 mg/kg (for ischemia/infarction)
Lidocaine infusion: 20 mcg/kg/minute IV (for ischemia/infarction)
Other treatments
Isoproterenol bolus: 1 to 2 mcg IV (for Brugada Syndrome or bradycardia-mediated torsades de pointes)
Isoproterenol infusion: 0.15 mcg/minute IV and titrate up to 0.3 mcg/minute as needed
Magnesium bolus: 2 g IV
Potassium bolus: 20 meq IV over 2 hours
Overdrive pacing: Start at 90 bpm and titrate upward as needed, usually not faster than 110 bpm
Propofol bolus: 50 mg IV
Propofol infusion: 100 mcg/kg/minute

Anti-arrhythmic medications and treatment for long-term management of electrical storm

Treatments
Preferred first choice therapy
Amiodarone
Oral load: 800 mg by mouth twice a day until 10 g total
Maintenance dose: 200–400 mg by mouth daily
β-blockers
Metoprolol tartrate: 25 mg by mouth twice aday, and can titrate dose upward every 2 weeks until limited by heart rate or blood pressure
Other antiarrhythmic therapy
Class I agents
Quinidine: 300 mg by mouth twice a day (for Brugada syndrome)
Mexiletine: 200 mg by mouth three times a day, and can titrate up every 3 days up to 400 mg by mouth three times a day (trough drug level ½ hr before the 6th dose should be check to avoid adverse effects)
Flecainide: 100 mg by mouth twice a day, and can titrate up to 200 mg by mouth twice a day (for CPVT; QRS duration on EKG should not be exceeding 25% from the baseline QRS duration)
Class III agents
Sotalol: 80 mg by mouth twice a day, and can titrate up every 3 days up to 160 mg twice a day (follow the QT interval)
Other treatments
Magnesium: replace to maintain serum magnesium concentration greater than 2.0 mg/dL
Potassium: replace to maintain serum magnesium concentration greater than 4.0 meq/L

Management algorithm for ventricular tachyarrhythmias based on QRS morphology



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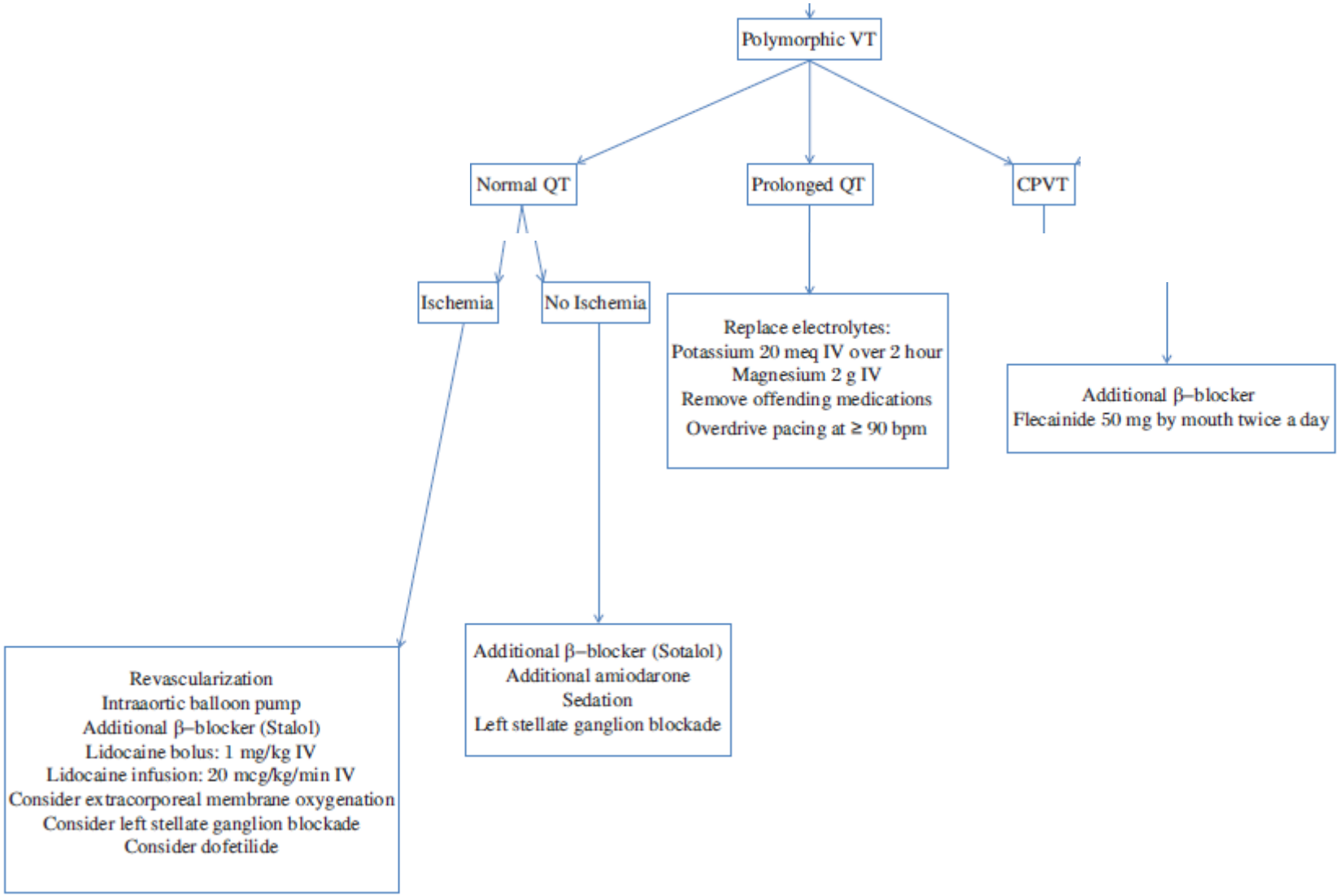

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