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## Endocardial Approach for Substrate Ablation in Brugada Syndrome

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### Abstract

Radiofrequency ablation (RFA) in Brugada syndrome (BrS) has been performed by both endocardial and epicardial. The substrate in BrS is not completely understood. We investigate the functional endocardial substrate and its correlation with clinical, electrophysiological and ECG findings in order to guide an endocardial ablation. Two patients agreed to undergo an endocardial biopsy and the samples were examined with transmission electron microscopy (TEM) to investigate the correlation between functional and ultrastructural alterations. About 13 patients ( $38.7 \pm 12.3$  years old) with spontaneous type 1 ECG BrS pattern, inducible VF with programmed ventricular stimulation (PVS) and syncope without prodromes were enrolled. Before endocardial mapping, the patients underwent flecainide testing with the purpose of measuring the greatest ST-segment elevation for to be correlated with the size and location of substrate in the electro-anatomic map. Patients underwent endocardial bipolar and electro-anatomic mapping with the purpose of identify areas of abnormal electrograms (EGMs) as target for RFA and determine the location and size of the substrate. When the greatest ST-segment elevation was in the third intercostal space (ICS), the substrate was located upper in the longitudinal plane of the right ventricular outflow tract (RVOT) and a greatest ST-segment elevation in fourth ICS correspond with a location of substrate in lower region of longitudinal plane of RVOT. A QRS complex widening on its initial and final part, with prolonged transmural and regional depolarization time of RVOT corresponded to the substrate located in the anterior-lateral region of RVOT. A QRS complex widening rightwards and only prolonged transmural depolarization time corresponded with a substrate located in the anterior, anterior-septal or septal region of RVOT. RFA of endocardial substrate suppressed the inducibility and ECG BrS pattern during  $34.7 \pm 15.5$  months. After RFA, flecainide testing confirmed elimination of the ECG BrS

pattern. Endocardial biopsy showed a correlation between functional and ultrastructural alterations. Endocardial RFA can eliminate the BrS phenotype and inducibility during programmed ventricular stimulation (PVS).

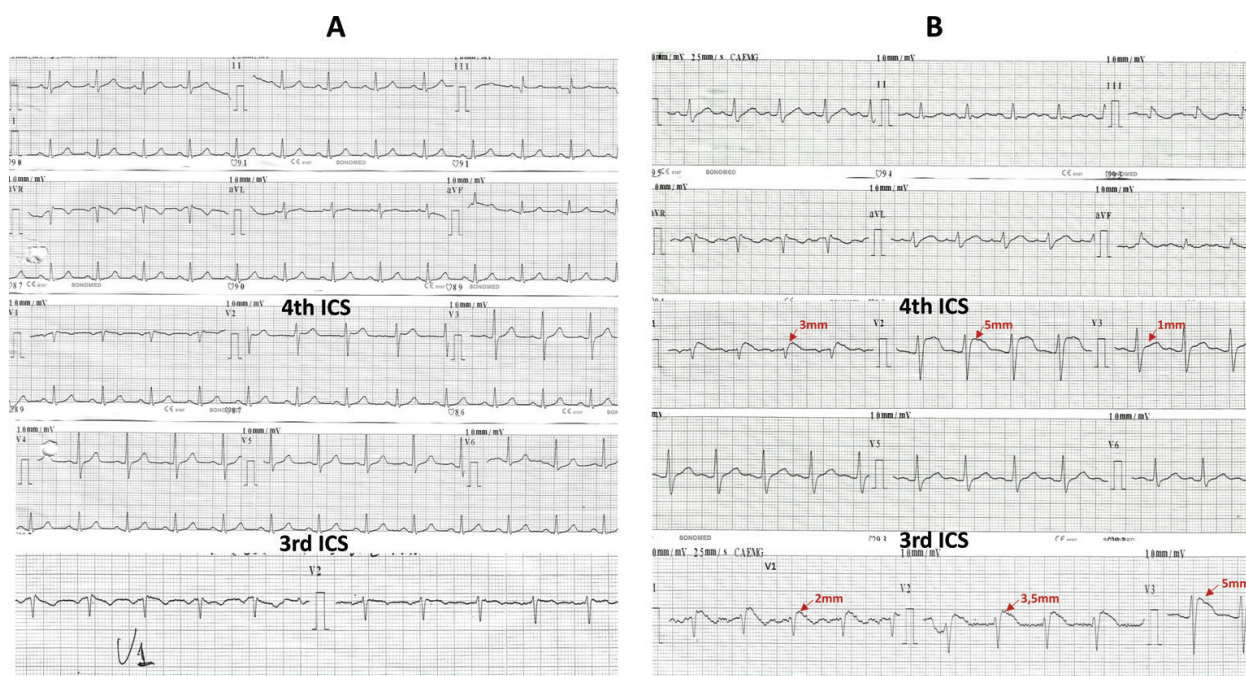
**Keywords:** Brugada syndrome, radiofrequency catheter ablation, electrocardiography, mapping, biopsy

## 1. Introduction

Since the original publication in 1992 [1], many researchers have tried to explain the mechanisms and substrate that causes an abnormal electrocardiographic (ECG) pattern and ventricular arrhythmias in Brugada syndrome (BrS) and few therapeutic options have been found. Initially three hypotheses were proposed for explain the mechanism and arrhythmias in BrS, the abnormal repolarization theory [2], the abnormal depolarization theory [3] and the abnormal expression of neural crest cells during cardiac development [4].

BrS is characterized by an elevated ST segment in the right precordial leads (V1–3) on the ECG and risk of sudden cardiac death (SCD) [1, 5]. The ECG 1 pattern is frequently intermittent and can be unmasked by the administration of a sodium channel blocker (**Figure 1**). The incidence of SCD in subjects with Brugada type 1 ECG pattern and no previous cardiac arrest is 2 per 1000 patients per year [6, 7].

At present, there are just two therapeutic strategies, which include implantable cardioverter-defibrillator (ICD) and/or chronic quinidine therapy [6, 7]. However, quinidine is not effective



**Figure 1.** Characteristic BrS ECG. A. In the N°3 patient the ECG at baseline show spontaneous and intermittent type 1 ECG BrS pattern. B. After flecainide test (400 mg, orally) [19].

in many patients and its use is frequently associated with intolerable adverse effects. ICD implantation may be effective in preventing SCD, and is currently recommended as a class I indication for symptomatic patients with type 1 Brugada ECG pattern. Unfortunately, ICD therapy in many patients is associated with inappropriate shocks (overall ICD complication rate is 9.1% and inappropriate shocks in BrS occur in 13.7%), lead fractures/failure, device infections and frequent ICD discharges by electric storms [6, 8, 9].

As an autosomal dominant disease with incomplete penetrance, BrS was initially linked to mutations in the SCN5A gene [9]. Currently, more than 450 pathogenic variants have been identified in 24 genes encoding sodium, potassium, and calcium channels or associated proteins [10, 11]. Known BrS-susceptibility genes can only partially explain the clinically diagnosed cases; therefore, many patients (65–70%) remain “genetically unresolved” [8, 9]. For many years, BrS has been considered a purely electric disease even if, more recently some authors have shown the presence of morphological and functional abnormalities (regional conduction slow in the endocardium and epicardium), predominantly located in the right ventricle outflow tract (RVOT) [12–14].

Radiofrequency ablation (RFA) has recently emerged as a therapeutic option in BrS patients of high risk. RFA in two previous reports was effective in preventing ventricular fibrillation (VF) in BrS [15, 16]. Two studies have recently shown fractionated systolic electrograms (EGMs) in epicardium of RVOT and RF normalized the ECG pattern and prevented ventricular fibrillation and ventricular tachycardia (VT/VF) occurrence in a short follow-up [17, 18].

## 2. Study population and risk factors

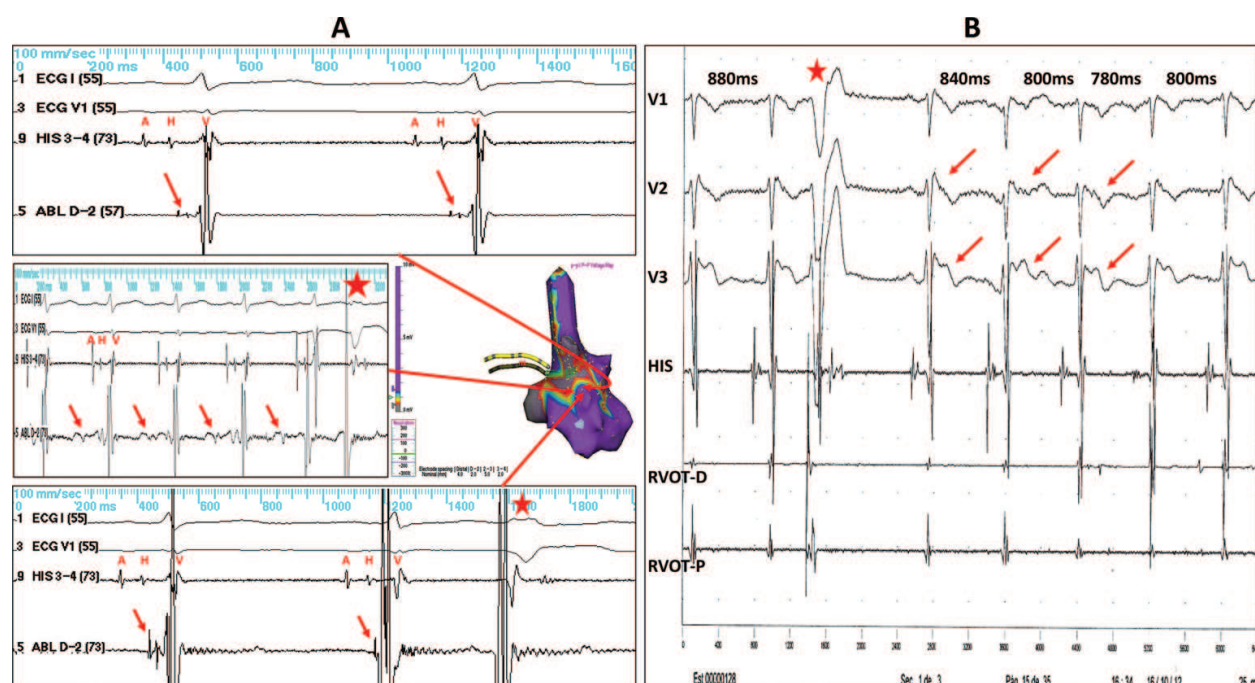
The arrhythmic events occur in patients who presented spontaneous type 1 ECG BrS pattern and syncope of presumed arrhythmic origin, so both are considered high-risk factors [6]. The risk of SCD in patients without ICD is 2 per 1000 patients per year [6, 7]. But unfortunately, the possibility of survival out of hospital is low if the first symptom is the SCD.

We in a prospective single-center study consecutively included 13 caucasian patients when they presented all three high-risk criteria: (1) documented spontaneous type 1 BrS ECG pattern, (2) syncope of probable arrhythmic cause (syncope was defined as a no traumatic and reversible loss of consciousness, and was considered of arrhythmic origin in the absence of a prodrome or triggering circumstances), (3) inducible VF with PVS [19]. These were associated with at least one of the following conditions: family history of SCD at age < 45 years, type 1 BrS ECG pattern in family members, early repolarization pattern, and/or nocturnal agonal respiration [6, 9]. Structural heart disease, systemic diseases and phenocopies was ruled out in each case on the basis of clinical history and extensive evaluation with 2D Echocardiography, tilt test, brain computed tomography, 24-hour ambulatory ECG monitoring, HIV test, coxsackie and parvovirus B19 test, Chagas disease test, myocardial perfusion and cardiac nuclear magnetic resonance. All patients had 5 points according to the risk score model currently proposed by Sieira et al. [20] (spontaneous type 1 ECG pattern =1 point, inducible VF =2 points and syncope =2 points). None had a history of SCD or documented spontaneous VT/VF and did not receive antiarrhythmic drugs. Patients were submitted to endocardial bipolar and



electroanatomic mapping and RFA. One month before of mapping and RFA, 10 patients accepted the implant of an ICD with class IIa indication [9]. **Table 1** shows the clinical characteristics of the study patients. About 13 patients with spontaneous type 1 ECG BrS pattern, symptomatic by syncope without prodromes, and VF induced during programmed ventricular stimulation (PVS) were enrolled and completed the study protocol. Five males (38.5%) and eight females (61.5%), with an average age of  $38.7 \pm 12.3$  years (range 19–58 years) were enrolled. Most patients (54%) had a family history of SCD and all patients experienced previous syncope episodes without prodromes. In four patients (31%) nocturnal agonal respiration and family history of ECG 1 BrS pattern were evident. All patients had a VRP  $\leq 200$  ms ( $180 \pm 13.6$  ms). A QRS complex duration  $>120$  ms in V1 or V2 leads ( $129.6 \pm 27$  ms) in six patients (46%) and a R wave with an amplitude  $\geq 3$  mm in aVR lead during flecainide testing ( $3 \pm 1.4$  mm) in seven patients (54%) was found. In five patients (38.5%) a HV interval to DI lead  $>55$  ms ( $53.4 \pm 21$  ms), in three patients a QRS fragmentation (23%) and in two patients a J wave (15.4%) were present. Interestingly, during bipolar mapping after premature ventricular contractions (PVCs), alternating T and J-wave and changes of the ST segment elevation were found (**Figure 2**).

Syncope constitutes an important diagnostic and therapeutic challenge in BrS. Approximately one-third of BrS patients present syncope. Some cases of syncope may be related to VF that terminates spontaneously. Vagal syncope is probably the most frequent cause of syncope in the BrS [21] and vagal hypertony may facilitate the onset of spontaneous VF in BrS [22]. Also symptoms suggesting of vagal syncope may also be observed in syncope of cardiac origin [23]. In our study, two patients (15%) after RFA had near-syncope with vaso-vagal prodrome and without arrhythmias in the ICD interrogation [19].



**Figure 2.** Endocardial mapping. A. The N° 3 patient in the peripheral zone of substrate show middle diastolic, pre-systolic and continuous EGMs. The split pre-systolic potential (red arrows) triggers PVC (red star). B. After PVCs (red star), alternating T and J wave are shown (electric turbulence). Also displays spontaneous ST segment elevation changes (red arrows) [19].

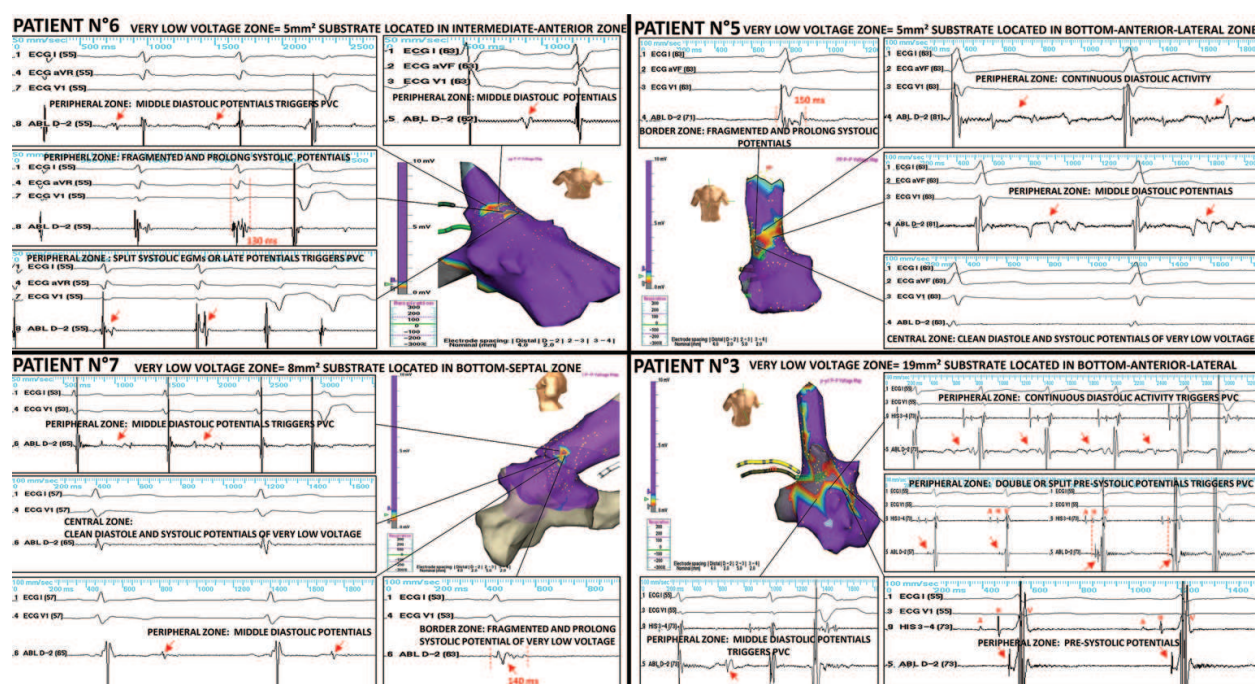
BrS is eight times more prevalent in males, probably for higher testosterone levels and a more prominent transient outward current (Ito). Males are at increased risk for developing a spontaneous type 1 ECG BrS pattern and VF during PVS. Nevertheless, because the majority of the asymptomatic patients are also male the gender is not an independent predictor of arrhythmic events [9, 24]. It is striking that eight of our patients (61.5%) were females. Five of these had between 38 and 58 years of age and menopausal symptoms, so we might suspect that lack of estrogens could induce the expression of phenotype [19].

### 3. Electrophysiological study and mapping: identification of functional substrate

Nademanee et al., found prolonged and fractionated late potentials in the anterior zone of epicardium of RVOT [17]. Recently, Brugada et al. in 14 inducible patients reported abnormal EGMs only in epicardium of the anterior free wall of right ventricle and in RVOT [18]. However, consistently we find a substrate in the endocardium of RVOT and RFA eliminates abnormal EGMs, ECG BrS pattern and inducibility during a median follow-up of  $44.7 \pm 15.5$  months in 13 patients. We saw the substrate not only in the anterior zone of RVOT but also in septal and lateral regions, but never in the posterior region [19]. Sunsaneewitayakul et al. reported late depolarization zones on the endocardial of RVOT. Endocardial RFA about these zones modified the ECG BrS pattern and suppress the VF storm [16]. Similarly, we reported areas with late depolarization, diastolic electrical activity and abnormal systolic EGMs. In our study high-density detailed endocardial electroanatomical and bipolar voltage mapping of right ventricle and RVOT was performed, using 3-dimensional (3D) mapping system En Site NavXTM under local anesthesia and sedation, during stable sinus rhythm [19]. AH and HV interval to DI and V2 lead and ventricular refractory period (VRP) were measured. Bipolar EGMs were filtered from 10 to 400 Hz and displayed at 100–200 mm/s speeds. Systolic EGMs with an amplitude  $\leq 1.5$  Mv, split or fractionated with a duration  $>80$  ms and delayed components extending beyond the end of QRS complex and accompanied by late potentials (LPs) were defined as abnormal. The EGMs found in the diastole were referred as “diastolic electrical activity”. The number of diastolic EGMs (separated by isoelectric line) in two successive sinus cycles was counted. PVS of RVOT with 3 cycle lengths (600, 500 and 400 ms) and up to two premature extrastimuli was performed. Premature extrastimuli was decreased in 20 ms step until a coupling interval of 200 ms or the VRP was reached or VF lasting  $>10$  seconds was induced. The induction with PVS up to two premature beats is independent predictors of poor prognosis with a high negative predictive value and was associated with increased risk, but has a controversial prognostic value. The lack of induction does not necessarily portend a low risk and hence clinical factors are the most important determinants [6, 20, 25, 26]. VF inducibility rate is highest in patients with BrS and syncope of unknown origin (80%), the lowest in asymptomatic patients (61.5%), and intermediate in patients with vasovagal syncope (70.5%) [26–29]. However, it is important to note that these observations correspond to the pre-ablation era of BrS and therefore, the PVS could be a good predictor of outcome after RFA [18]. In our patients the endocardial RFA of diastolic electrical activity and abnormal systolic EGMs suppressed the type 1 ECG BrS pattern and inducibility with PVS, making the patients asymptomatic, as was previously reported for the epicardial RFA [17, 18].

We identified three zones of substrate according to amplitude of the systolic EGMs: central very low voltage zone  $<0.5$  mV, peripheral low voltage zone of  $0.5$ – $1.5$  mV (border) and normal voltage zone  $>1.5$  mV [19]. The central zone of substrate using filling scaling was measured in  $\text{mm}^2$  and located in the RVOT. Areas showing low-amplitude signals were mapped with greater point density. Abnormal endocardial electroanatomic voltage maps, characterized by very low-voltage EGMs with clean diastoles in the central area of substrate were found. Only three patients (23%) during bipolar mapping showed fragmented systolic EGMs of low-voltage ( $\leq 1.5$  mV) with duration greater of 80 ms between central and peripheral zone (border zone) of voltage mapping. As shown in **Figure 3**, only in the peripheral zone of substrate the endocardial diastolic EGMs (mean  $6.7 \pm 1.4$  EGMs in two successive sinus cycles) were present. Overall, the median baseline very low voltage or central area of substrate ( $\leq 0.5$  mV) was  $14.2 \text{ mm}^2$  (SD = 10.5) (**Table 1**).

It is important to note, that epicardial mapping may not recognized a substrate located in the septal zone of RVOT. In addition, during epicardial mapping the interposition of fat tissue between the epicardium and the exploratory catheter could decrease the amplitude of the potentials recorded, giving false areas of low voltage. Our study only inclusion 13 patients and may be considered a small size sample [19]. However, our results are consistent allowing us to reach reliable conclusions. We not performed genetic studies. However, it is unlikely that this could affect our observations because mutations have been described in over 24 genes and BrS-susceptibility genes can only partially explain the clinically diagnosed cases.



**Figure 3.** Endocardial electroanatomic maps and location of abnormal EGMs. Double systolic EGMs, late potentials, middle diastolic potentials and continuous diastolic activity in peripheral zone that triggers PVCs is displays. Prolonged and fragmented systolic EGMs of low voltage in border zone in three patients can be observed. In the central zone of substrate observe clean diastole with very low-voltage systolic potentials. The N°3 patient displays single and split pre-systolic potentials in peripheral zone of substrate which triggers PVCs [19].



Patient	1	2	3	4	5	6	7	8	9	10	11	12	13	Total	%	Mean	SD
Age	41	33	57	55	58	27	46	26	24	19	38	38	41			38.7	12.3
Sex	M	F	F	M	F	M	M	F	F	M	F	F	F	F = 8 M = 5	F = 61.5%-M = 38.5%		
Spontaneous type 1 ECG pattern	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	13	100%		
Syncope without prodromes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	13	100%		
Nocturnal agonal respiration	No	No	No	No	Yes	No	Yes	No	Yes	No	No	Yes	No	4	31%		
Palpitations	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	13	100%		
Family history SCD	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No	No	7	54%		
Family history BrS	No	Yes	No	No	No	No	No	No	Yes	Yes	Yes	No	No	4	31%		
VRP ≤ 200 ms	180	180	160	200	160	180	200	180	160	180	180	200	180	13	100%	180 ms	13.6
QRS duration in V2 lead (> 120 ms)	160	105	120	180	120	120	140	100	90	140	170	140	100	6	46%	129.6 ms	27
R wave in aVR lead (≥ 3 mm) (#)	3	4.5	2	2.5	1.5	1	4	4	1.5	6	3	4	1	7	54%	3 mm	1.4
QRS fragmentation	No	Yes	No	No	No	No	No	Yes	No	No	No	No	Yes	3	23%		
J wave	No	No	No	No	No	No	Yes	No	No	No	Yes	No	No	2	15.4%		
HV interval to DI lead (>55 ms)	60	57	40	120	57	40	46	35	45	45	55	35	59	5	38.5%	53.4 ms	21
HV interval to V2 lead (>55 ms)	40	40	35	80	45	40	46	35	40	45	55	35	46	1	7.7%	44.8 ms	11.5
Follow-up (months)	66	63	56	53	51	54	45	46	45	43	28	12	19	13	100%	44.7	15.5
CDI implant	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	10	77%		
Biopsy	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes	2	15%		
Very low-voltage AREA(≤ 0.5 mV) in (mm <sup>2</sup> )	23	8	19	42	5	4	8	10	19	10	8	25	4	13	100%	14.2 mm <sup>2</sup>	10.5
N° endocardial diastolic EGMs IN 2 successive cycles sinus (≥4 EGMs)	8	8	5	7	7	9	6	6	9	6	6	7	4	13	100%	6.7	1.4
Procedure time (min)	120	110	100	90	120	95	105	95	100	100	160	90	170			112	24.5
Fluoroscopy time (min)	15	10	10	10	15	10	12	13	12	10	27	10	25			13.7	5.5

M = male, F = female, SD = standard deviation, (#) = during flecainide test, VRP = ventricular refractory period.  
Source: Ref. [19].

**Table 1.** Basal characteristic and risk factors.



Although the results of mapping and RFA were good, we do not perform epicardial mapping and do not ignore the possibility that a portion of the substrate can remain present after ablation.

In addition, we found pre-systolic potentials as was previously reported by Haissaguerre et al. [15]. We showed with TEM Purkinje fibers in RVOT (**Figures 2 and 3**) [19]. These could be involved in the origin of pre-systolic potentials and genesis of early-onset PVCs that can trigger VT or VF, by spontaneous depolarization or micro-reentry circuit in the Purkinje network [30].

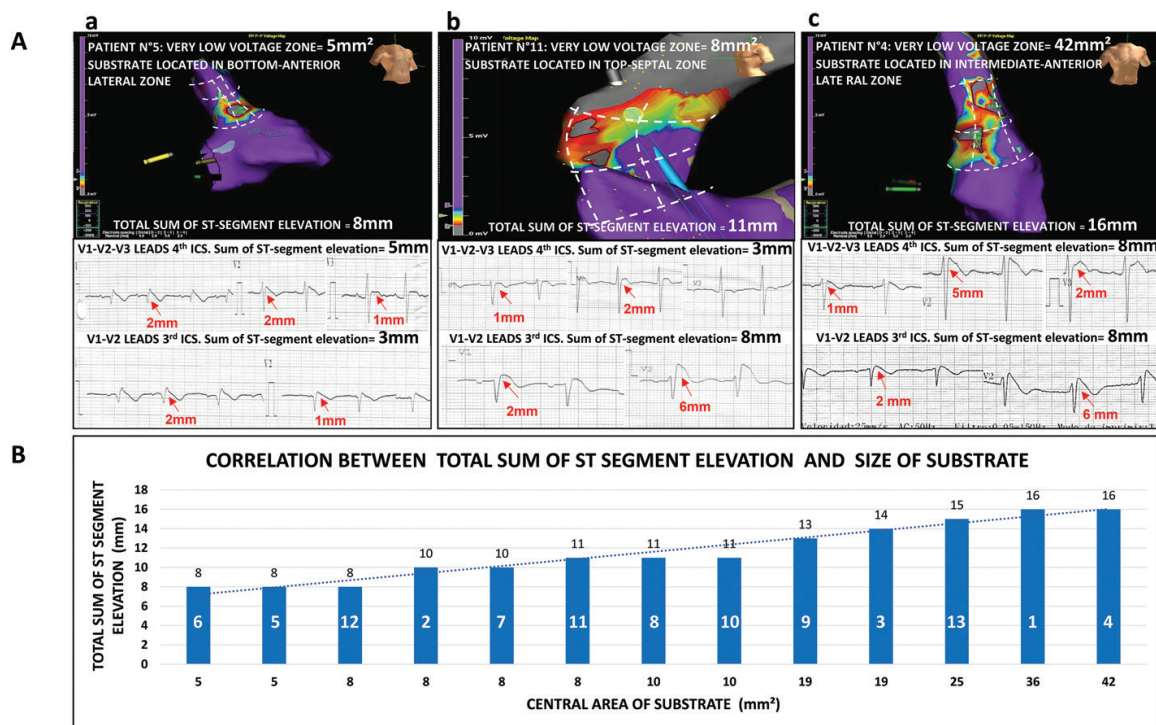
## 4. Electrocardiographic analysis

### 4.1. Size of substrate and ST-segment elevation

In the BrS the mechanism of ST segment elevation has been explained by the repolarization theory (decreased of Na<sup>+</sup> and/or Ca<sup>++</sup> channel function with a prominent Ito current in epicardium of RVOT generates a transmural voltage gradient), or the depolarization theory (disturbances in depolarization of RVOT can be cause of delayed conduction and ST segment elevation) [18, 20]. Nevertheless, the ECG changes are actually explained by the theorem of solid angle, where a substrate larger increases the magnitude of the ST segment elevation [31]. In 13 patients of high risk we have analyzed QRS complex duration, R wave amplitude in aVR lead, presence of fragmented QRS (f-QRS) and end-QRS slur or notch in DI, aVL, DII, DIII and aVF leads with J point peak  $\geq 0.2$  mv with descending ST segment, corresponding to an early repolarization or “J wave” [19]. Before of endocardial mapping the patients were underwent flecainide testing (400 mg, orally) with the purpose of measuring the greatest ST-segment elevation. The partial greatest ST-segment elevation in millimeters (ST-segment elevation in V1 + V2 leads in the third ICS and ST-segment elevation in V1 + V2 + V3 leads in fourth ICS), and total sum of greatest ST-segment elevation (ST segment elevation in V1 + V2 leads in the third ICS plus ST-segment elevation in V1 + V2 + V3 leads in fourth ICS) were measured. (**Figure 4-A**). Correlation between size and location of substrate in the electro-anatomic map and the ST-segment elevation were analyzed. As shown in **Figure 4** and **Table 2**, with a cut-off  $\geq 13$  mm in the total sum of ST segment elevation two variants were found: (1) A total sum of ST-segment elevation  $< 13$  mm ( $n = 8$ , 61.5%, mean  $9.6 \pm 1.3$  mm) corresponded to a central area of substrate of  $7.7 \pm 1.8$  mm<sup>2</sup>; (2) A total sum of ST segment elevation  $\geq 13$  mm ( $n = 5$ , 38.5%, mean  $15 \pm 1.1$  mm) corresponded to a central area of substrate of  $28.2 \pm 9.2$  mm<sup>2</sup> ( $p < 0.001$  for correlation of ST segment elevation and correlation of central area of substrate, with a value  $> 0.90$  of ROC curve).

Brugada et al. during electro-anatomic mapping with administration of a sodium channel blocker showed an increase in the size of the low voltage [18]. In concordance, our observations suggest that the total sum of ST segment elevation during flecainide testing would approximately determine the substrate size. In addition, the ECG leads with greater ST segment elevation would locate the substrate in the RVOT [19].

Morita et al. (145 patients who experienced syncope or had VF events) proposes ECG risk markers for the initial and recurrent episodes of VF in symptomatic patients with BrS. The f-QRS,



**Figure 4.** Correlation between ST segment elevation and substrate localization. A. With the administration of sodium channel blocker, a greater magnitude of total sum of ST segment elevation corresponds to a greater very low voltage area of substrate, and allows its location in the longitudinal plane of RVOT. (a) The location of the substrate in the bottom zone of RVOT correspond to a greater sum of ST segment elevation in fourth ICS vs. third ICS (5 vs. 3 mm). (b) The location of the substrate in the top zone of RVOT correspond to a greater sum of ST segment elevation in third ICS vs. 4th ICS (8 vs. 3 mm). (c) The location of the substrate in the intermediate zone of RVOT corresponds to a sum of ST segment elevation of equal magnitude in third ICS and fourth ICS (8 mm and 8 mm). B. The graph shows the correlation between linear increase of total sum of ST segment elevation and substrate size. The blue bars indicate each patient [19].

inferolateral early repolarization and complete RBBB were associated with occurrence of ventricular tachyarrhythmia in the symptomatic patients [34]. Our population show in three patients a QRS fragmentation (23%) and in two patients a J wave (15.4%) [19].

#### 4.2. Location of substrate in the longitudinal plane

Nademanee et al. found functional substrate in the anterior zone of epicardium of RVOT [17]. Brugada et al. in 14 inducible patients reported a functional substrate in epicardium of RVOT and anterior free wall of right ventricle [18].

In our study a high-density endocardial electroanatomical mapping of right ventricle and RVOT was performed [19]. Taking the pulmonary valve as upper limit and the supraventricular crest as lower limit in the longitudinal plane the RVOT was divided in top and bottom. As shown in **Figure 4-A** and Table II, we have found three variants: (1) When the substrate was located in the top region of RVOT, it corresponded with the greater sum of ST-segment elevation in V1-V2 leads in the 3rd ICS (n = 5, 38.5%); (2) When the substrate was located in the bottom region of RVOT (n = 5, 38.5%), it corresponded with the greater sum of ST-segment elevation in V1-V2-V3 leads in the 4th ICS; (3) When the substrate was located in

Patient	ST-segment with	Total sum of	Size of low	Location of substrate
	>elevation (mm)	ST-segment Elevation (mm)	voltage Area (mm <sup>2</sup> )	In the longitudinal and
	V1-V2 leads V1-V2-V3 leads			Transverse plane
	Third ICS 4TH ICS			
1	V1 = 2 V1 = 2	16	36	Bottom Anterior-lateral
	V2 = 4 V2 = 7			
	V3 = 1			
	V1 = 3 V1 = 1			
2	V2 = 4 V2 = 2	10	8	Top Anterior-lateral
	V3 = 0			
	V1 = 2 V1 = 3			
3	V2 = 3 V2 = 5	14	19	Bottom Anterior-lateral
	V3 = 1			
	V1 = 2 V1 = 1			
4	V2 = 6 V2 = 5	16	42	Intermediate Anterior-lateral
	V3 = 2			
	V1 = 2 V1 = 2			
5	V2 = 1 V2 = 2	8	5	Bottom Anterior-lateral
	V3 = 1			
	V1 = 2 V1 = 0			
6	V2 = 2 V2 = 2	8	5	Intermediate Anterior
	V3 = 2			
	V1 = 1 V1 = 1			
7	V2 = 3 V2 = 4	10	8	Bottom Septal
	V3 = 1			
	V1 = 3 V1 = 1			
8	V2 = 5 V2 = 2	11	10	Top Anterior
	V3 = 0			
	V1 = 2 V1 = 3			
9	V2 = 3 V2 = 4	13	19	Bottom Anterior-septal
	V3 = 1			
	V1 = 5 V1 = 1			
10	V2 = 3 V2 = 2	11	10	Top Anterior
	V3 = 0			

Patient	ST-segment with	Total sum of ST-segment	Size of low voltage	Location of substrate
	>elevation (mm)	Elevation (mm)	Area (mm <sup>2</sup> )	In the longitudinal and
	V1-V2 leads V1-V2-V3 leads			Transverse plane
	Third ICS 4TH ICS			
11	V1 = 2 V1 = 1 V2 = 6 V2 = 2 V3 = 0 V1 = 2 V1 = 1	11	8	Top Septal
12	V2 = 3 V2 = 2 V3 = 0 V1 = 3 V1 = 3	8	8	Top Anterior-septal
13	V2 = 4 V2 = 5 V3 = 0	15	25	Intermediate Anterior
Mean and SD	3 ± 1.3 2.3 ± 1.5	<13 (n = 8, 61.5%) 9.6 ± 1.3 ≥13 (n = 5, 38.5%) 15 ± 1.1	7.7 ± 1.8 28.2 ± 9.2	
p value		<0.001	<0.001	

Source: [19].

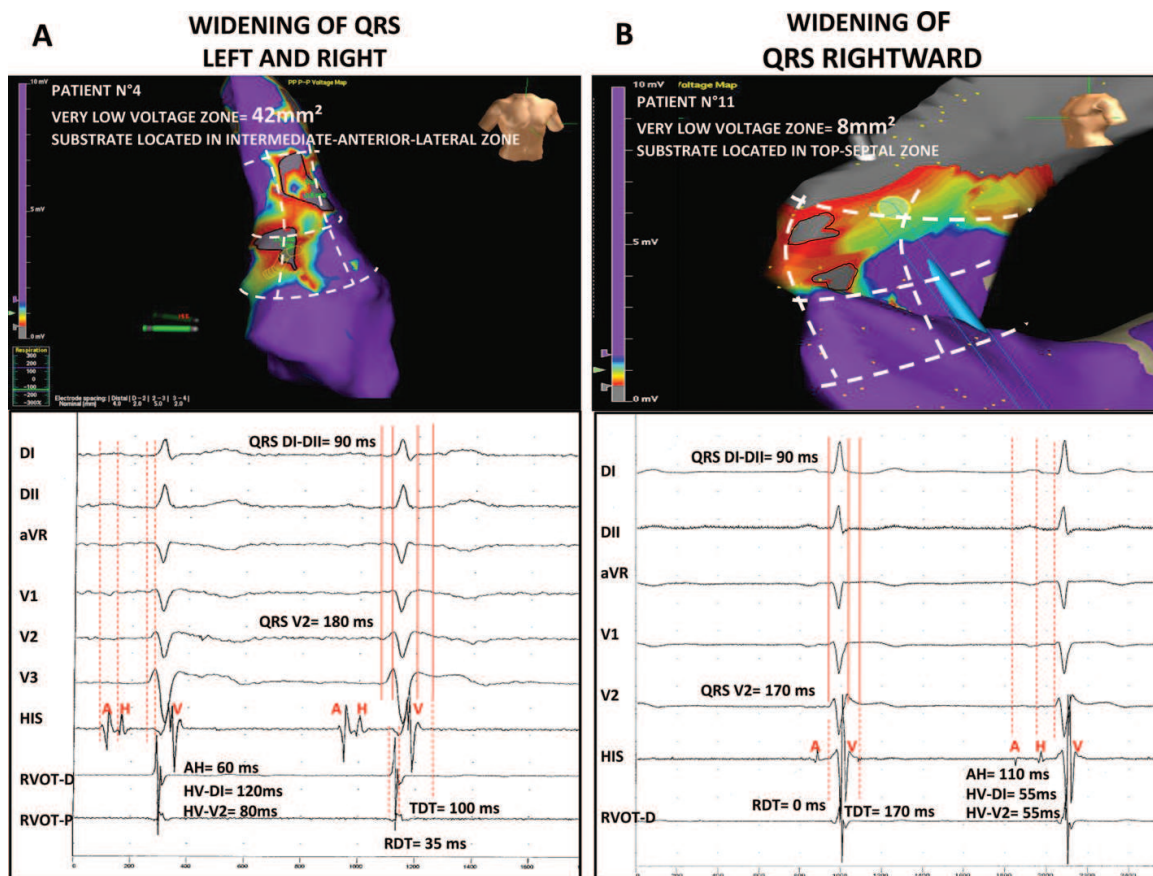
**Table 2.** Correlation between sum of ST-segment elevation, location and size of low voltage area.

the intermediate region of RVOT (n = 3, 23%), the sum of ST-segment elevation was of equal magnitude in the 3rd and 4th ICS (n = 3, 23%).

#### 4.3. Location of substrate in the transverse plane

In our study during endocardial electroanatomical mapping, in the transverse plane an anterior, lateral, posterior and septal areas were identified [19]. During endocardial bipolar mapping, the regional depolarization time (RDT) from the endocardial EGM of right ventricular inflow tract (RVIT) recorder by the catheter located at the site of His, until the beginning of endocardial EGM of RVOT, recorded by the catheter located in the RVOT was measured. A value from 0 to 10 ms was considered normal. Moreover, the trans-mural depolarization time (TDT) of RVOT from the beginning of endocardial EGM of RVOT until the end of QRS complex in V2 lead was measured. The TDT measured at DI was considered as normal value. As shown in **Figure 5**, we have found two variants were found: (1) When the substrate was located in the anterior lateral region of RVOT (n = 5, 38.5%), the HV interval measured to DI lead (mean 70.6 ± 24 ms) was longer than the HV interval to V2 lead (mean 50 ± 15 ms). This was accompanied with widening of the QRS complex in its initial and final parts (widening of QRS left and right) in V1 and V2 lead. We defined this as “mixed delay of depolarization of RVOT”.

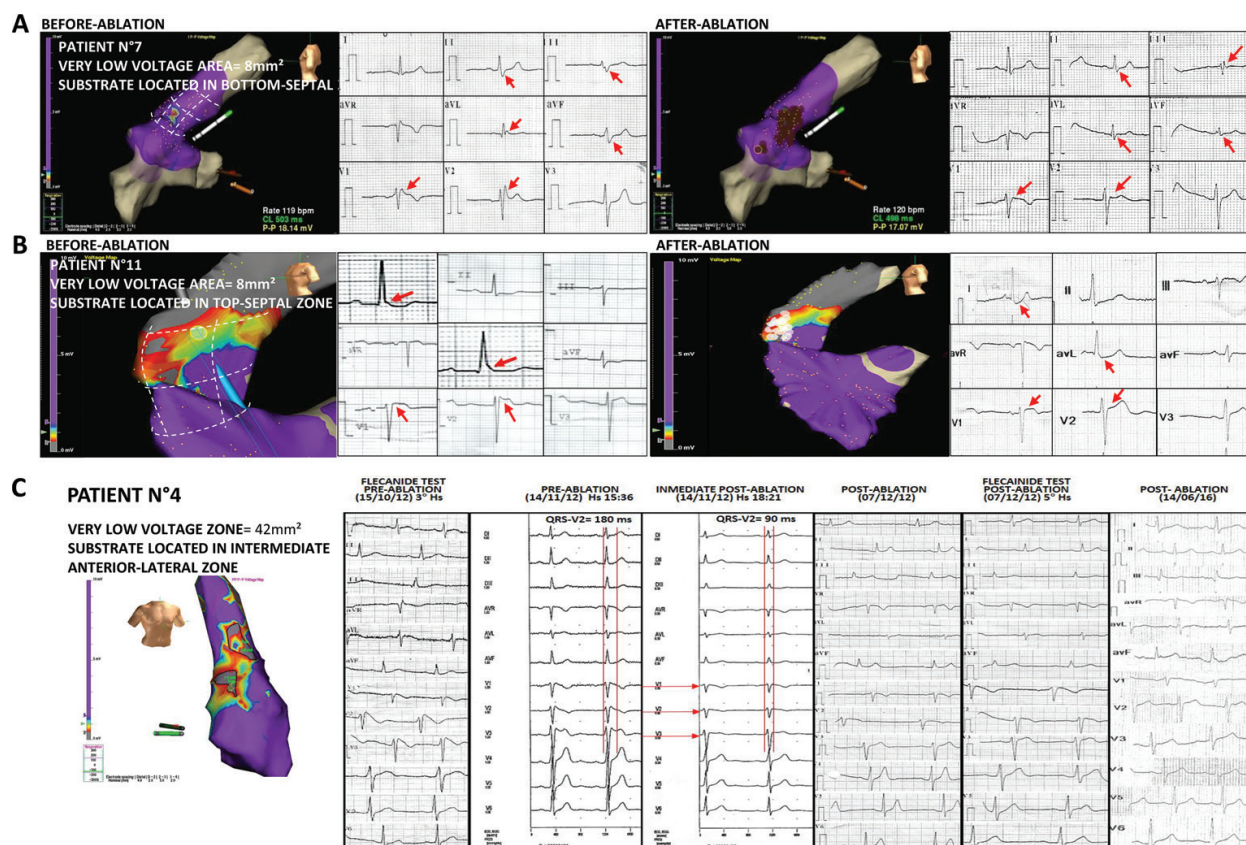




**Figure 5.** Location of substrate in transverse plane of RVOT. A. The N°4 patient displays a substrate located in the anterior-lateral zone of RVOT which corresponds to a widening of QRS complex to left and right. The HV interval to DI lead is longer (120 ms) than the HV interval to V2 lead (80 ms), while RDT and TDT are prolonged. B. The N°11 patient displays a substrate located in the septal zone of RVOT which correspond only to a widening of end QRS complex. The HV interval to DI and V2 leads is equal (55 ms) and only TDT is prolonged [19].

Simultaneously, TDT and RDT were prolonged, because early depolarization of RVOT occurs. (2) When the substrate was located only in the anterior part (30.8%), or anterior-septal (15.4%) or exclusively in the septal region (15.4%) of RVOT, the HV interval measured to DI and V2 leads showed no increase in its duration (mean  $42.6 \pm 6$  ms and  $41 \pm 6.5$  ms, respectively) and the widening of QRS was only rightward (widening QRS rightward). Moreover, the endocardial EGM of RVIT and RVOT, and beginning of QRS complex in DI-V1-V2 lead they were activated simultaneously, indicating that there is no RDT delay, while TDT of RVOT was prolonged of dynamic manner. We defined this as “end delay depolarization of RVOT”.

Was report that 11% of patients with BrS have early repolarization pattern in the inferior-lateral leads and a more severe phenotype [32]. Interestingly, as shown in **Figure 6** we found in two patients who had a substrate of exclusively septal location, showed end-QRS notching or slurring pattern. When the substrate was located in the bottom-septal zone of RVOT (patient N°7) only end-QRS notch in aVL lead and slurred S-wave in DII, DIII and a VF leads was observed (**Figure 6-A**). Whereas, when the substrate was located in the top-septal zone of RVOT (patient N°11) an end-QRS slur in DI and aVL leads was observed (**Figure 6-B**). Our observations suggest that a location of substrate in septal region of RVOT, with beginning of the depolarization at the



**Figure 6.** RFA effects on the ECG. A. The N°7 patient displays a substrate located in bottom septal zone of RVOT. Before RFA a type 2 ECG BrS pattern, end-QRS notch in aVL lead and slurred S wave in DII, DIII and aVF leads are present. It disappears after RFA (red arrows). B. The N°11 patient displays a substrate in the top septal zone of RVOT. Before RFA a type 1 ECG BrS pattern and end-QRS slur in DI and aVL leads are present. It disappears after RFA (red arrows). C. Before RFA the flecainide test showed a type 1 ECG BrS pattern. The QRS complex duration in V1 and V2 leads was 180 ms, while in DI was 90 ms (red lines). Immediately after ablation, the duration of QRS complex in V2 lead decreased to 90 ms and ECG BrS pattern disappears (red arrows). After RFA the flecainide test not induced type 1 ECG BrS pattern. The ECG at 3.8 years follow-up persist normal [19].

endocardium correlated with the presence of end-QRS notching or slurring pattern in inferior or/and lateral leads by slow conduction. As shown in **Figure 6 A and B** the endocardial RFA of substrate produced their disappearance [19]. Normally the epicardium is electropositive with respect to electronegative endocardium creating a current flow of endocardium to epicardium. When activation spreads from endocardium to epicardium, in a context of slow conduction, the J wave coincides with the notch in the epicardial AP mediated by the Ito current and it is recorded by ECG. Conversely, when the activation begins in the epicardium, the J wave disappears hidden by the QRS complex [33]. Consequently, our observations lead us to think that the J wave depends more of late depolarization than early repolarization as was suggested by other authors.

## 5. Effects of RFA on the ECG BrS pattern and substrate

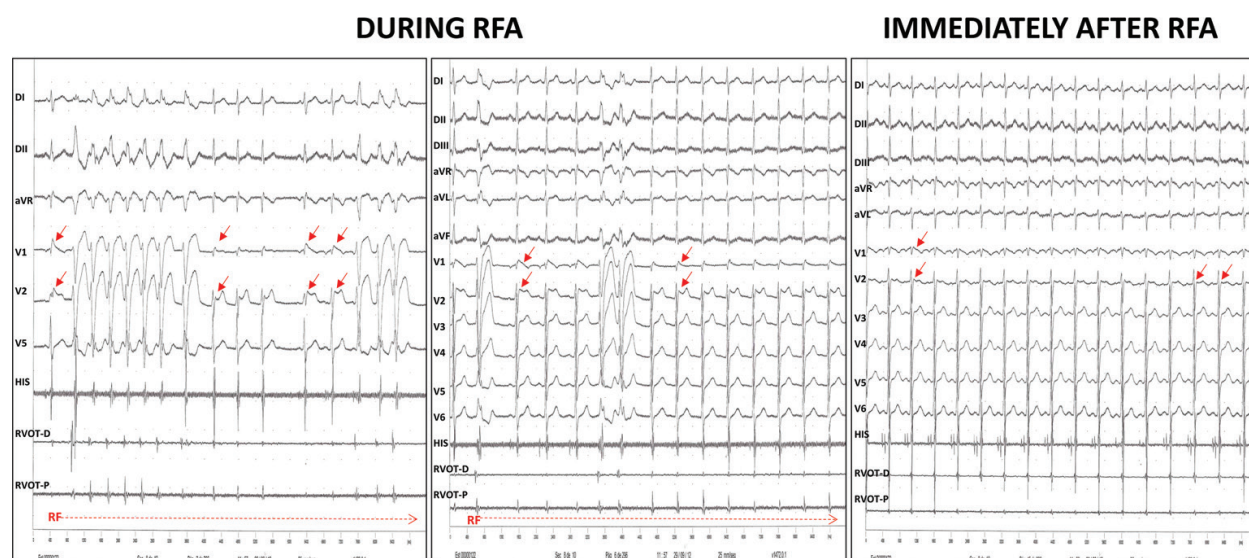
Endocardial and epicardial RFA has been proposed as a new strategy to prevent SCD and VT/VF in BrS patients of high risk. Nademanee et al. found that RFA on prolonged and



fractionated late potentials in the anterior zone of epicardium of RVOT normalized the ECG BrS pattern and prevented VT/VF in all but one patient during a follow-up of  $20 \pm 6$  months [17]. Recently, Brugada et al. in 14 inducible patients reported abnormal EGMs only in epicardium of the anterior free wall of right ventricle and in RVOT. RFA eliminated both ECG BrS pattern and inducibility, with a median follow-up of 5 months [18].

In our study, the endocardial RFA in 13 patients resulted in normalization of the ECG BrS pattern, disappearance of end-QRS notching or slurring and suppression of inducibility in all patients during a mean follow-up of  $47.7 \pm 15.5$  months (**Table 1**) [19]. About 30 days after RFA a flecainide testing did not develop ECG BrS pattern. Seven patients who entered to procedure with spontaneous type 1 ECG pattern showed ECG normalization at the end of the procedure. Immediately after RFA was applied, activity and varying degrees of changes in ST segment were observed. With following applications of RFA the ECG pattern progressively decreased (**Figure 7**). After RFA local abnormal diastolic EGMs completely disappear and systolic EGMs were replaced by residual very low voltage areas. The mean time of procedure and fluoroscopy were  $112 \pm 24.5$  and  $13.7 \pm 5.5$  minutes, respectively (**Table I**). Postprocedure, predischARGE, and follow-up 12-lead ECG confirmed the absence of BrS ECG pattern (**Figure 6C**). The patients were asymptomatic and free of arrhythmic events in the 24-hour ambulatory ECG monitoring and in follow-up the ICD interrogation. Two patients (15%) had a near-syncope with prodrome at 24 of 46 months and at 18 of 36 months of follow-up respectively, without arrhythmias in ICD interrogation.

Sunsaneewitayakul et al. reported that endocardial RFA on the late depolarization zones modified the ECG BrS pattern in three patients and suppress the VF storm in four patients, during follow-up of 12–30 months [16]. Similarly, we obtained suppression of inducibility, normalization of BrS ECG pattern and early repolarization pattern with endocardial RFA of



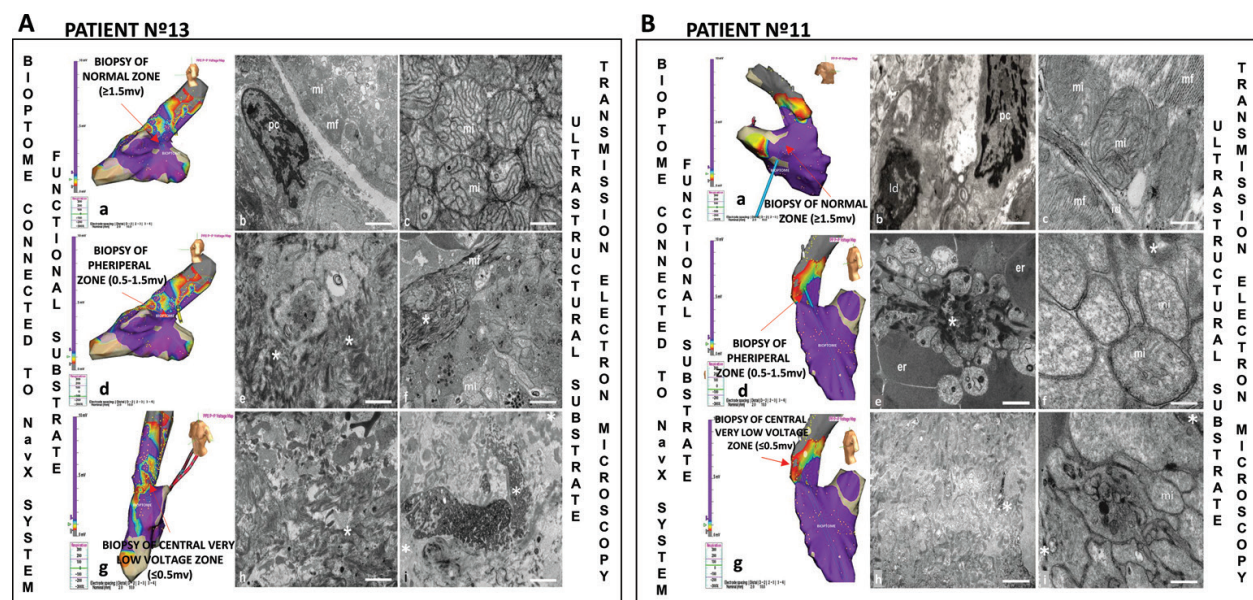
**Figure 7. Effects of radiofrequency ablation on ECG.** In the N°3 patient during endocardial RFA, intense activity and varying degrees of ST segment changes are shown. The ECG pattern progressively decreases with the following applications (red arrows). After RFA the local abnormal diastolic EGMs completely disappeared and systolic EGMs were replaced by residual low voltage areas [19].

areas with late depolarization, diastolic electrical activity and abnormal systolic EGMs [19]; probably by substrate homogenization and transmural lesion of the thin wall of RVOT (mean 3 mm). In addition, as show **Figures 2 and 3** we found pre-systolic potentials as was previously reported by Haissaguerre et al. [15]. In our patients the endocardial RFA of these potentials suppress PVCs and inducibility on PVS [19].

## 6. Correlation between functional and ultrastructural substrate

Coronel et al. show in a heart explanted of a BrS patient, fibrosis with epicardial fat infiltration as well as conduction slow without transmural repolarization differences [35]. Furthermore, interstitial fibrosis, fat tissue and myocyte disorganization with reduced gap junction expression in the presence of fractionated and unfractionated low voltage systolic EGMs in the endocardium and epicardium of RVOT was reported with optical microscopy [36–38].

In two patients, before RFA and after right internal jugular venous access through a steerable sheath we advanced a biptome to RVOT and connected to 3-dimensional (3D) mapping system [19]. Guiding by electroanatomic and voltage map two samples of endo-myocardial biopsies of the three previously defined zones of substrate was obtained. Samples were fixed in 4% glutaraldehyde and 0.1% sodium phosphate (pH 7.4) for transmission electron microscopy (TEM) study as was described previously [39]. As show **Figure 8** the ultrastructural substrate and functional substrate were correlated [19]. In the **Figure 8A**, the patient N°13 in (a), (d) and (g) shows electro-anatomic and voltage map (functional substrate) with a central area of substrate of 25 mm<sup>2</sup> located in the intermediate-anterior zone of the RVOT and the biptome



**Figure 8.** Correlation between functional and ultrastructural substrate. On the left side the electro-anatomic and voltage map (functional substrate) and biptome connected to the navigation system is shown. On the right side the ultrastructural substrate is shown. Scale Barr: 3.33, 2.2 and 1.42  $\mu\text{m}$ ; mitochondria (mi); myofibrils (mf); Purkinje cell (pc); myofibrillar rests (\*); lipofuscin deposit (ld); intercalated disk (id); remains of erythrocytes (er) [19].



connected to the navigation system. In (b) and (c) on the right side can be seen the ultrastructural substrate which corresponds to normal zone with mitochondria, myofibrils, and a Purkinje cell of normal characteristics. In contrast, in the peripheral zone of substrate (e and f) note that when approaching to pathological area, cytoplasmic vacuolization, myofibrillar and mitochondrial disorganization with myofibrillar residue can be observed. The (h) and (i) corresponds to the central zone, which depicts strong vacuolization and cell destruction with intense cytoplasmic disorganization and myofibrillar residue. In the **Figure 8B**, the patient N° 11 in (a), (d) and (g) shows the voltage and electro-anatomic map (functional substrate) with central area of substrate of 8mm<sup>2</sup> located in the top-septal zone of the RVOT. In (b) and (c) on the right side can be seen the ultrastructural substrate which corresponds to normal zone with normal characteristics of mitochondria, myofibrils, and a Purkinje cell. The approaching to pathological area in the peripheral zone of substrate (e and f), myofibrillar disorganization, cytoplasmic vacuolization, swelling and disappearance of mitochondrial crests, myofibrillar rests and remains of erythrocytes were observed. The (h) and (i) corresponds to the central zone showing strong vacuolization and cell destruction and myofibrillar residue. Fat replacement, lymphocytic infiltration, Chagasic myocarditis, collagen tissue or apoptotic bodies were not observed.

It is important to note that when we approach to pathological areas progressive cell damage was observed. In the central zone of substrate low voltage systolic EGMs coincided with strong cell destruction and cytoplasmic disorganization. The peripheral zone of substrate with cell damage, mitochondrial swelling and myofibrillar residue without apoptotic bodies coincided with late potentials, diastolic and/or presystolic activity (**Figures 2 and 3**). These findings support mitochondrial energy loss as possible non-apoptotic progressive tissue damage and death cell. Our results suggest the interesting possibility that substrate could be generated by an abnormal expression of neural crest cells localized in RVOT during cardiac development. Because an epicardial and endocardial substrate was demonstrated, our findings together with those of other researchers support the probability of a transmural substrate.

## 7. Mechanisms of arrhythmias

Two theories suggest that an abnormal repolarization (local re-excitation by phase 2 reentry in the epicardium) or a defect of the depolarization (disturbances in depolarization of RVOT can cause conduction delay) may be responsible of phenotype and VF in BrS [40–43]. However, in BrS the arrhythmias are usually polymorphic VT or VF, and these cannot be supported by macro-reentry mechanisms. VF depends of a firing focus initiated by early or delayed after-depolarization or a micro-re-entry [44]. Surviving cells surrounded by fibrosis has demonstrated to be responsible of slow conduction and reentry in inhomogeneous scars [45]. The residual electrical activity within scar was reported as delayed or isolated EGMs, late potentials or diastolic EGMs and their elimination during sinus rhythm was effective to prevent VT/VF [45]. In peripheral zone of substrate when a sufficient degree of cell damage was reached such as we found with TEM and resting potentials are reduced the polymorphic VT/VF may occur. This event could be originated through a firing focus or by multiple wavelets from a reentrant microcircuit, and would explain the “diastolic electrical activity” observed in our patients.

In addition, we found pre-systolic potentials as was previously reported by Haissaguerre et al. [15]. As show **Figure 8**, the Purkinje fibers in RVOT could be involved in the origin of pre-systolic potentials and in genesis of early-onset PVCs that can trigger VT or VF, by spontaneous depolarization or micro-reentry circuit in the Purkinje network [30].

## 8. Conclusion

In patients with BrS of high risk the substrate RFA may be a potential option of treatment. We successfully ablated the substrate of BrS from the endocardium based on the electrophysiological and ultrastructural findings. Our data together with the observations of other researchers suggest a transmural substrate, contributing to future definition of the arrhythmogenic substrate in BrS. As many phenotypes are involved in BrS, it is not unthinkable that different substrates may exist in BrS. ECG analysis during administration of a sodium channel blocker allows approximately determined the size and location of substrate. Careful endocardial mapping allows identify late potentials, presystolic and diastolic EGMs as a new risk marker to guide an endocardial substrate RFA, probably with the same results what a more complex epicardial ablation. A comparative study between endocardial and epicardial RFA should be performed.

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## Conflict of interest

The authors declare none conflict of interest.

## Abbreviations

AP	action potential
BrS	Brugada syndrome
ECG	electrocardiogram
EGMs	electrograms
EPS	electrophysiology study
f-QRS	fragmented QRS

ICD	implantable cardioverter defibrillator
LPs	late potentials
PVC	premature ventricular contractions
PVS	programmed ventricular stimulation
RFA	radiofrequency ablation
RP	refractory period
RV	right ventricle
RVIT	right ventricular inflow tract
RVOT	right ventricular outflow tract
SCD	sudden cardiac death
TEM	transmission electron microscopy
VF	ventricular fibrillation
VRP	ventricular refractory period
VT	ventricular tachycardia

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