Long-term follow-up of implantable cardioverter-defibrillators in children: Indications and outcomes

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Abstract

Background. Validation data of the use of implantable cardioverter-defibrillators (ICD) in the pediatric population is insufficient, with limited follow-up periods.

Objectives. The aim of the study was to report on 17 years of experience with implantable cardioverter-defibrillator (ICD) therapy in children and young adults.

Material and methods. This retrospective review included patients below the age of 18 years at the time of ICD implantation between May 2000 and December 2017. For the statistical analysis, the sample was divided into groups by gender and the type of indications for ICD implantation (primary vs secondary prevention).

Results. The study group included 20 children (8 female, 12 male) who underwent ICD implantation for primary or secondary prevention of sudden cardiac death (SCD). The average age at the time of the initial procedure was 15.6 years (range: 3.8–17.7 years). Primary electrical disease (PED) was present in 9 patients, cardiomyopathy (CMP) in 9 and 2 others had congenital heart defects (CHDs). The median follow-up time was 6.7 years (range: 0.4–12.5 years). The outcomes of ICD therapy were analyzed. No differences between the sexes were found in terms of treatment strategy effectiveness ($p > 0.05$). The girls were more often treated as primary prevention ($p = 0.009$). After implantation, all the patients were on optimal pharmacotherapy. Altogether there were 126 ICD interventions in 11 patients, including 23 inadequate interventions (IA) in 2 children (18.2%). Three children (15%) died due to electrical storms. In the per-procedure analysis, the overall freedom rate from ICD lead replacement was 90%, 80% and 57% at 1, 5 and 10 years of observation, respectively.

Conclusions. Implantable cardioverter-defibrillator implantation indications in children are more heterogeneous in comparison to adult population. In the pediatric population undergoing ICD implantation, the treatment strategy is influenced by gender. The rate of inappropriate ICD discharges (IA) in our group of pediatric patients was low. Rigorous pharmacotherapy and individual ICD programming seemed of paramount importance. Lead malfunctions LF constituted the most prevalent complication observed.

Key words: sudden cardiac death, implantable cardioverter-defibrillator, pediatric cardiology

Introduction

The authors present their own experience in the use of implantable cardioverter-defibrillator (ICD) therapy in children, with one of the longest follow-up periods conducted in a single center from pediatrics to adulthood. Validation data for ICD use in pediatric populations is insufficient, with limited follow-up periods, and is primarily based on isolated clinical cases, single-center studies, registries, and a few comparison studies with ICD use in adults. Therefore, this paper is of high educational value to young scientists who at the beginning of their scientific and medical career need to deepen their medical knowledge and stay up-to-date with current guidelines and trends in medicine worldwide.

The implementation of ICD therapy has significantly decreased the number of sudden cardiac deaths (SCD) in the adult population.^{1–3} According to the American Heart Association (AHA) and American College of Cardiology (ACC) recommendations, the secondary prevention indications for ICD therapy are the same in children as in adults. The main indications for ICD implantation in the pediatric population are primary electrical heart disease (PED), cardiomyopathy (CMP), congenital heart defect (CHD) post-surgical correction, ventricular tachycardia (VT), and idiopathic ventricular fibrillation (VF) in patients with an anatomically normal heart.^{4,5}

As there are no randomized pediatric ICD studies and because experience in the pediatric population is limited to small retrospective case series with short follow-up periods only, statistically significant results are difficult to obtain in this field. We hypothesized that single-center observations of a relatively large non-uniform pediatric group of patients with one of the longest-term follow-ups could contribute to better care of young patients.

The aim of the study was to analyze the indications for ICD implantation, programming issues and treatment options for any arrhythmic and device complications (failure rate and extractability of ICD leads implanted in patients below 18 years of age) in a follow-up period of up to 17 years, which in turn could also improve our understanding of the related issues.

Material and methods

The study was designed as a single-center retrospective analysis of all patients aged below 18 years who underwent ICD implantation between May 2000 and December 2017. The study was approved by the institutional review board and fully complies with the declaration of Helsinki (protocol No. NKBBN/7/2017).

Demographic information, diagnoses, indications for ICD implantation, age and weight at implantation, as well as device and lead information and the patients' course were collected. The indications for ICD implantation for SCD were established according to the guidelines and

recommendations.^{4,6–8} Primary prevention indications were determined either according to the respective guidelines and recommendations or on an individual basis with special reference to the underlying cardiac condition.^{9–13} At the time of implantation, all the ICD systems were tested according to standard clinical practice and contemporary guidelines.^{14,15} Follow-up data included in-house follow-up as well as examinations by collaborating specialists. The patient follow-up started at the time of the 1st implantation and lasted until death by any cause, or the date of the last documented device interrogation, or the end of the study in December 2017. The initial ICD check took place within the first days post implantation, after which follow-ups were performed at 4–6 weeks, 12 weeks and every 6 months thereafter, or more often if needed. Follow-up visits took place in the outpatient ICD clinic according to the standard protocol, and consisted of interrogation and retrieval of all data stored since the previous visit and routine measurements of pacing and sensing parameters. In addition, some patients were subject to remote monitoring of their ICD systems.

The follow-up data was evaluated for the presence of both appropriate (AI) and inappropriate shocks (IA), ICD programming information, any history of supraventricular tachycardia (SVT), and the use of antiarrhythmic (AA) medications. Inappropriate shocks were defined as shocks delivered for reasons other than VT or VF meeting programmed detection criteria. The details of the ICD programming were recorded at the time of either IA or the most recent follow-up visit if no IA occurred. The detection rate was recorded in beats per minute (bpm). The detection duration was recorded in either the number of beats or the number of seconds, depending on the device programming/manufacturer. For comparison purposes, detection duration in seconds was converted into duration in beats by using the programmed upper detection rate and the detection duration.

Ineffectiveness of the combined pharmacological therapy and ICD implantation was defined as no impact on the mortality rate in this specific pediatric group.

The technical outcome of ICD therapy was also analyzed retrospectively, and included lead malfunctions and complications. We identified implantation procedure complications and late follow-up complications as a composite of the following: mechanical complications caused by an ICD system, infection and inflammatory reaction due to the presence of the cardiac device or the implantation procedure, iatrogenic pneumothorax, accidental puncture or laceration, post-operative hemorrhage or hematoma, and other complications described in the literature.

Statistical analysis

Statistical analyses were performed using Wizard Pro v. 1.9.22 software (Evan Miller, Chicago, USA). Categorical variables were expressed as numbers (n) and percentages. Continuous variables were expressed as means $\pm$ standard deviation (SD) or medians (minimum–maximum),

depending on the distribution. The normality of distribution was tested using the Shapiro–Wilk test. The paired Student t-test and Wilcoxon signed-rank test were used for repeated measures, while the unpaired Student t-test and Mann–Whitney test were used for independent samples. For multiple comparisons, proper analysis of variance (ANOVA) or Friedman's test were used. Categorical data was compared using the χ^2 test. A p-value <0.05 was considered significant for all tests.

For the statistical analysis, the sample was divided into groups by gender and the type of indications for ICD implantation (primary vs secondary prevention).

Results

Patient characteristics/demographics

The clinical and demographic characteristics of the study group, including indications for ICD implantation, are presented in Tables 1 and 2. Two patients moved to another town and are under cardiological follow-up in another center. The distribution of primary and secondary prevention indications and types of cardiovascular disease (CVD) in the study group are presented in detail in Fig. 1.

Initial indications for ICD implantation

The indication for ICD implantation was resuscitated sudden cardiac arrest (SCA) in 12 patients (60%, secondary prevention), while ICDs for primary prevention were implanted in 8 patients (40%) (Table 2). The main symptoms leading to ICD implantation in the whole study group were transient loss of consciousness (TLOC) in 5 children (25%) and palpitations in 2 (10%). The other 13 patients (65%) were asymptomatic. In 5 of the 7 symptomatic children echocardiographic (ECG) examinations revealed left ventricle ejection fraction (LVEF) below 20% and Holter ECG recordings showed non-sustained VT (nsVT). In 3 cases, electrophysiological studies were performed before

the implantation procedure due unknown causes of SCA. Cardiac magnetic resonance imaging (MRI) was performed in 4 patients: 2 with CMP and 2 after resuscitated SCA. In 2 of these patients, there were no abnormalities; in one patient, a diagnosis of non-compact left ventricle (NCLV) was confirmed; in the other, non-ischemic dilated cardiomyopathy (DCM) was eventually diagnosed.

Anti-arrhythmic therapy

Before ICD implantation, 14 children (70%) were on AA medication, and after implantation, all 20 children (100%) were. The most common therapy was beta-blockade (nadolol, metoprolol), either alone or in combination with class III AA drugs (amiodaron, sotalol), as shown in Tables 2 and 3. The optimal treatment for heart failure (HF) according to current guidelines and recommendations was used before ICD implantation in all the children with CMP.^{12,16}

Table 2. Clinical data, indications for ICD implantation, therapy, and outcomes in terms of gender

Variable	Female	Male	p-value
Number of patients	8 (40%)	12 (60%)	0.371
Age at 1 st intervention [years]	16.2	16.4	0.905
ICD indication			
primary	6 (75%)	2 (17%)	0.009
secondary	2 (25%)	10 (83%)	
Diagnosis			
PED	3 (38%)	6 (50%)	0.300
CMP	5 (63%)	4 (33%)	
CHD	0 (0%)	2 (17%)	
Symptoms			
TLOC	2 (25%)	3 (25%)	0.049
palpitations	2 (25%)	0 (0%)	
asymptomatic	4 (50%)	9 (75%)	
Pharmacotherapy			
before ICD implantation	8 (100%)	6 (50%)	0.017
post ICD implantation	all	all	
Pharmacotherapy			
II	3 (38%)	6 (50%)	0.435
III	1 (13%)	0 (0%)	
AA therapy + HF	4 (50%)	6 (50%)	
Deaths	1 (13%)	2 (17%)	0.761
HTX	1 (13%)	0 (0%)	0.209
ICD interventions			
AI	3 (38%)	5 (42%)	0.621
IA	1 (12%)	1 (8%)	
both	1 (12%)	0 (0%)	
none	3 (38%)	6 (50%)	
Time to first AI [days]	361	163	1.000
Time to first IA [days]	1,664	350	0.667
Therapy effectiveness			
effective	4 (50%)	5 (42%)	0.714
non-effective	4 (50%)	7 (58%)	

ICD – implantable cardioverter-defibrillators; CMP – cardiomyopathy; CHD – congenital heart defect; PED – primary electrical disease; TLOC – transient loss of consciousness; AA therapy – antiarrhythmic therapy; HF – heart failure; HTX – heart transplantation; AI – appropriate interventions; IA – inappropriate interventions.

Table 1. Clinical and demographic characteristics of the study group

Characteristic	Value
Number of patients	20
Median age of implantation [years]	15.6 (3.8–17.7)
Gender	8 F (40%)/12 M (60%)
Body weight at initial implantation [kg]	52.1 ±18.6
Indications for ICD implantation	
primary/secondary	6 (30%)/14 (70%)
Mean follow-up period [years]	6.5 ±4.8
Deaths	3 (15%)
Heart transplantation	1 (5%)

F – female; M – male; ICD – implantable cardioverter-defibrillator.

Fig. 1. Indications for implantable cardioverter-defibrillator (ICD) implantation and cardiovascular disease (CVD) in the study group

Technical aspects of ICD implantation

All the initial procedures were performed under general anesthesia. The most common initial approach for ICD implantation was transvenous (used in 19 children). Among the implanted systems there were 14 single-chamber and 5 dual-chamber ICDs. A biventricular device (cardiac resynchronization) was placed in 1 patient. Single-coil leads were placed in 17 children and dual-coil leads in 3.

In 3 children, a single-chamber ICD was placed in the abdominal region and an active-fixation ICD lead was simultaneously implanted through the subclavian vein. The incision was made parallel to the linea and then to the tendon of the rectus abdominalis, and the ICD was placed under that muscle in a subrectus pocket. Then, the ICD lead was tunneled subcutaneously to the subclavian region and was placed through the cephalic vein in the apex of the right ventricle. The ICD “active can” was connected to the lead (or leads), all electrical parameters were measured again and a defibrillation test was performed.

A defibrillation threshold test (DFT) was performed according to current guidelines. The mean DFT result at primary implantation was 15 J (range: 6–20 J). The VF detection duration was programmed initially between “18 out of 24” and “75 out of 100” based on the reason for ICD implantation. The initial R wave amplitude was 8.9 ± 4 mV. In our only patient with an epicardial lead, the DFT was 10 J. All shocks were programmed to the maximum energy output of the devices.

There were no acute intraprocedural or early post-procedural complications at the initial ICD implantations.

The effects of gender

To check whether gender had any impact, we examined potential differences between females and males in this study (Table 2). Loss of consciousness or family history were significantly more frequent reasons for establishing the diagnosis and qualification for SCD prevention in boys ($p = 0.042$) than

in girls, while palpitations were significantly more frequent reasons among girls. Girls were more likely to receive pharmacotherapy prior to ICD implantation ($p = 0.017$) and were more often treated in primary prevention ($p = 0.009$). No differences ($p > 0.05$) between the sexes as to the effectiveness of treatment with ICD or the effectiveness of pharmacotherapy were found.

Primary vs secondary prevention of SCD

Patients were also divided into groups depending on the type of indication for ICD implantation – primary vs secondary prevention (Table 3), and our comparative

Table 3. Clinical data, etiology, arrhythmia occurrence, EF, and results of the treatment used in the study group in terms of ICD implantation for secondary vs primary prevention

Prevention of SCD	Primary	Secondary	p-value
Number of patients	8	12	0.371
Sex			
F	2 (17%)	6 (75%)	0.009
M	10 (83%)	2 (25%)	
Diagnosis			
CHD	0 (0%)	2 (17%)	0.007
CMP	7 (88%)	2 (17%)	
PED	1 (13%)	8 (67%)	
EF			
>50%	2 (25%)	12 (100%)	0.001
<50%	6 (75%)	0 (0%)	
Pharmacotherapy			
I	0	0	0.043
II	1 (13%)	8 (67%)	
III	1 (13%)	0 (0%)	
AA therapy + HF	6 (75%)	4 (33%)	
Therapy effectiveness			
effective	6 (75%)	3 (25%)	0.028
non-effective	2 (25%)	9 (75%)	

ICD – implantable cardioverter-defibrillators; SCD – sudden cardiac death; CMP – cardiomyopathy; CHD – congenital heart defect; PED – primary electrical disease; EF – ejection fraction; AA therapy – anti-arrhythmic therapy; HF – heart failure.

analysis showed several statistically significant differences between these groups. As mentioned earlier, ICDs were implanted in girls for primary prevention significantly more often than for secondary ($p = 0.009$). Also, there were significant differences ($p < 0.001$) between the reasons for reporting to a cardiologist among the patients treated in primary prevention (with no history of SAC) compared to those in secondary prevention (with a history of resuscitated SAC). Additionally, in primary prevention, patients with CMP were treated more often compared to patients with normal heart anatomy ($p = 0.009$) or those with CHD (tetralogy of Fallot, Ebstein's anomaly) ($p = 0.039$).

Patients treated for primary prevention had significantly higher ($p = 0.011$) incidence of nonspecific intraventricular conduction delays (Fig. 2) compared to those treated for secondary prevention, who more often had right bundle branch blocks (RBBBs) or incomplete right bundle branch blocks (IRBBBs).¹⁷ One child had a left bundle branch block (LBBB). Ventricular arrhythmias of at least 3 morphologies ($p < 0.001$) and documented episodes of VF were more frequent among the patients qualified for secondary

prevention ($p = 0.006$). Patients with reduced left ventral contractility (LVEF $< 50\%$) more frequently had ICDs implanted as primary prevention ($p < 0.001$).

If the primary cause of the referral to a cardiologist was TLOC, treatment (ICD and pharmacotherapy combined) was more effective ($p = 0.035$); if the reason for the referral was family history, it was ineffective ($p < 0.001$). Other reasons for referrals were not found to affect the effectiveness of the combined treatment. The type of prevention (primary or secondary) was also a factor influencing the effectiveness of the treatment ($p = 0.028$).

It was also found that in secondary prevention, arrhythmia was more complex: nsVT/VT/VF, as opposed to VPB in primary prevention).

Appropriate and inappropriate device discharge

An analysis of ICD intervention in terms of AI and IA or a lack of intervention was carried out (Table 4). There were 126 ICD interventions in 11 patients (55%): 102 (81%)

Fig. 2. ECG demonstrates intraventricular non-specific conduction block in a 6-year old patient qualified for the primary implantable cardioverter-defibrillator (ICD) implantation due to dilated cardiomyopathy (DCM). Interventricular conduction delay (IVCD) is determined on the basis of the current recommendation¹⁷

Table 4. Appropriate and inappropriate device discharges

Variable	Total number of patients having any interventions	AI	IA	Both interventions (AI & IA)	p-value
Number of patients	11	8	2	1	0.020
Sex					0.621
female	5 (63%)	3 (38%)	1 (13%)	1 (13%)	
male	6 (50%)	5 (42%)	1 (8%)	0 (0%)	
ICD indication					0.632
primary	5 (63%)	4 (50%)	1 (13%)	0 (0%)	
secondary	6 (49%)	4 (33%)	1 (8%)	1 (8%)	
Diagnosis					0.528
PED	4 (44%)	2 (22%)	1 (11%)	1 (11%)	
CMP	5 (55%)	4 (44%)	1 (11%)	0 (0%)	
CHD	2 (100%)	2 (100%)	0 (0%)	0 (0%)	
Time to the 1 st intervention [days] (range)	350 (6–2,412)	163 (6–2,412)	637 (350–2,691)	82	

ICD – implantable cardioverter-defibrillator; PED – primary electrical disease; CMP – cardiomyopathy; CHD – congenital heart defect; AA therapy – anti-arrhythmic therapy; AI – appropriate interventions; IA – inappropriate interventions.

ICD Model: Marquis VR 7230
Serial Number: PKD609671S

May 19, 2006 16:16:31
9967 Software Version 4.0
Copyright Medtronic, Inc. 2002

VT/VF Episode #5 Report

Page 1

ID#	Date/Time	Type	V. Cycle	Last Rx	Success	Duration
5	May 05 10:13:25	VF	370 ms	VF Rx 6	No	2.8 min

Fig. 3. The record of electrogram (ECG) from implantable cardioverter-defibrillator (ICD) demonstrates inappropriate shocks (IA) due to oversensing of T-wave

AIs in 8 children (40%) and 22 (18.2%) IA in 2 patients (10%); 1 teenager had 1 AI (0.8%) and 1 IA (0.8%) intervention (Fig. 3). The rate of IA due to non-optimal programming of the device was 5%; oversensing of the T-wave caused 10%; pace/sense lead dislocations were the cause of 5%; and HV lead failure (LF) caused 10% of IAs. There were no interventions at all in 9 patients (45%). The median time before the 1st intervention (of any kind) was 350 days (range: 6–2,412 days).

ICD-system-related complications and actions taken to solve them

During the follow-up period, 1 girl with arrhythmogenic right ventricle CMP (ARVC) underwent heart transplantation 6 months after ICD implantation, at the age of 17. A patient with an ICD implanted for primary prevention of SCD gave a birth to a healthy neonate 7 years after the ICD implantation. None of the patients in our study group had the ICD removed permanently, and there were no infections of the implanted ICD systems during the follow-up period. In 2 cases, remote monitoring was used; the devices documented atrial fibrillation in 1 case and nsVT in the other. In both cases, the pharmacological AA therapy was then modified.

During the follow-up period 3 of the patients died. The 1st patient was an adolescent with catecholaminergic polymorphic ventricle tachycardia (CPVT), who received his ICD in 2000 (the 1st patient in our study) at the age of 15; he died 3 years after ICD implantation due to therapy-resistant VF. He was on maximal pharmacotherapy at that time (a combination of class II and class III AA drugs). The ICD in this case was a Medtronic Micro Jewel II, model 7223 Cx (Medtronic plc, Dublin, Ireland), implanted in a left abdominal pocket with the lead tunneled

from the infraclavicular region to the pocket. The implant defibrillation threshold (DFT) was 15 J measured using a biphasic waveform. The DFT was rechecked within 2.5 months after implantation and remained unchanged. The lead impedance at implant was 45 Ω . The 1st AI was delivered just 1 week after implantation. The device was programmed for the VT and VF zones, and 34 J shocks. At the time of the patient's therapy-resistant VF, the VF detection rate was 240 bpm, the detection number count was 24 out of 32, and the VT zone was 200 bpm and 75 out of 100.

The 2nd patient that died, a girl with DCM who received her ICD as a bridge to a heart transplant at the age of 16, died 6 months after implantation due to therapy-resistant VF (an electrical storm).

The 3rd patient that died, a boy with ARVC, underwent ICD implantation at the age of 6 as a bridge to a transplant. He died 4 months after implantation due to HF resistant to pharmacotherapy. The 1st AI in this case (ATP due to FVT) was documented 56 days post implantation.

Data concerning ICD-system related complications and actions taken to solve them is presented in Table 5. Six patients (30%) experienced LF, 2 patients (10%) experienced failures of pace/sense leads and 5 patients (25%) experienced failures of high-voltage (HV) leads. In 2 patients, more than 1 LF took place. In total, 7 re-interventions were performed from 0.1 to 11.3 years (median: 7.4 years) from the initial system implantation; 6 of them were related to malfunctions of Sprint Fidelis HV leads (Medtronic plc). In the per-procedure analysis, the overall freedom from HV lead replacement was 90%, 80% and 57% during 1, 5 and 10 years of observation, respectively.

During the follow-up period, the whole ICD system was replaced in 4 cases using Cook lead extraction tools (Cook Medical LLC, Bloomington, USA).

Table 5. Complications due to HV lead dislocation or failure

Patient ID	Year of initial surgery	Re-intervention		
		Time to [years]	Cause	Procedure performed
2	2005	11.3	HV LF – Sprint Fidelis (6949) (high threshold on FU visit)	Extraction with Cook, new HV Lead implanted (Biotronic Linx Smart S65)
3	2005	0.1	HV lead dislocation – Sprint Fidelis (6949)	Extraction with traction, new HV lead implanted (Medtronic 6949)
		10.4	HV LF – Sprint Fidelis (6949) (high threshold on FU visit)	Extraction with Cook of old leads, new leads implanted (Biotronic Protego ProMRI and Medtronic CapSureFix Novus 5076-52 cm)
4	2005	0.5	HV lead dislocation – Sprint Fidelis (6949)	Extraction with traction, new HV lead implanted (Medtronic 6949)
	2006	9.7	HV LF – Sprint Fidelis (6949) (high threshold on FU visit)	Extraction with Cook, new HV lead implanted (Biotronic Linx S65) Complication: embolisation of subclavian vein
9	2007	1.8	HV LF – Sprint Fidelis (6931) (IA shocks due to HV lead fracture)	Extraction with traction, new HV lead implanted (Biotronic Linx S65)
12	2008	7.4	HV LF – Biotronic Linx S65 (high threshold on FU visit)	Extraction with Cook Evolution, implantation of new leads (Biotronic Linx and Medtronic 5076-52 cm)

HV – high voltage; LF – lead failure; IA – inappropriate intervention.

Discussion

The present data from a long-term single-center registry of children and adolescents undergoing ICD implantation offers one of the longest follow-up periods under the same supervisor in the same center in the available literature. Furthermore, this patient population presents a remarkable incidence of appropriate therapy delivery and displays the long-term course of children with ICDs in detail, particularly regarding device complications.

Effects of gender

We divided our study cohort according to gender. The groups did not differ significantly in terms of age or diagnosis (both organic heart disease and electrical pathology); however, in a more detailed statistical analysis, there were several significant differences between the groups. This may suggest that girls pay more attention to the feeling of heart “palpitations”, while boys get medical care only after incidents of unconsciousness. As a secondary result of this difference, girls were more likely to receive pharmacotherapy prior to ICD implantation and were more often treated for primary prevention. In the literature, we did not find any studies that analyzed this aspect. Interestingly, no differences between the sexes were identified in our study in terms of the effectiveness of either ICD treatment or pharmacotherapy. There are only few available studies concerning this subject.¹⁸ In their study, Sears et al. investigated differences between male and female pediatric ICD patients in terms of quality of life (QOL), and their conclusion was that “the observed differences in lower psychosocial, physical, and cardiac-specific QOL between female and male patients suggest that female patients feel particularly limited across these domains of functioning”.¹⁹

Secondary vs primary prevention of SCD

Implantable cardioverter-defibrillator implantation techniques have been simplified considerably in recent years thanks to significant reductions in the dimensions of modern generators and the use of transvenous leads.^{9,10,13,14,20} In the past, ICD implantation was mainly performed for secondary prevention of SCD, but nowadays ICDs are often implanted for primary prevention, although this is still a field of great controversy.^{4,8,13,21,22} We studied several factors to determine the effectiveness of primary vs secondary prevention of SCD.

With regard to pharmacotherapy, the 2 analyzed groups differed significantly. Those treated for primary prevention were more likely to receive pharmacotherapy before implantation ($p = 0.017$), and they more often received AA drugs (class III) or combination therapy: class III and optimal HF treatment according to current guidelines and recommendations. The patients in the secondary prevention

group primarily had β -blocker therapy.²³ This was mainly related to differences in the underlying diseases.

Comparing the groups in which the treatment was assessed as effective or ineffective, it was found that they differed in terms of certain characteristics. Firstly, in the group characterized by ineffective treatment, patients with CMP were more frequent, while in the effective treatment group, more patients with congenital malformations or PED with normal heart anatomy were found ($p = 0.025$). To some extent, this observation might have been influenced by the guidelines and how the patients were qualified for treatment.

Secondly, the type of prevention (primary or secondary) was a factor determining the effectiveness of the treatment ($p = 0.028$). It was revealed that in secondary prevention of SCD, complex arrhythmia was diagnosed more frequently than in primary prevention.

The statistical analysis also showed that ventricular arrhythmia morphology was a factor determining the effectiveness of ICD interventions and combination therapy ($p = 0.004$). The treatment used was significantly less effective in the presence of 2 ventricular beat morphologies (both LBBB and RBBB). In addition, reduced LVEF was a significant ($p = 0.002$) parameter determining overall treatment efficacy (pharmacological treatment and ICD interventions). Apart from the above, no other factors related to the effectiveness of therapy were found.

Appropriate and inappropriate device therapy

Implantable cardioverter-defibrillator shocks delivered for reasons other than life-threatening ventricular arrhythmias, known as IA, occur frequently in ICD-equipped patients.^{1,24–26} Pediatric patients and patients with CHD have a particularly high rate of IAs, with the largest studies reporting up to 20% of patients receiving them, mainly due to higher heart rates in younger patients, a higher risk of lead malfunction due to more active lifestyles and longer follow-up periods.^{26–30} That is why in our center, since the very first case, we have been programming devices individually, based on the patients' individual characteristics, in order to achieve the best results.^{1,7,31}

In our study, 3 patients (15%) suffered from a total of 23 IAs. Specifically, the rate of IAs due to non-optimal programming of the device was 5%; due to T-wave oversensing 10%; due to pace/sense lead dislocations 5%; and due to HV LF in 10% of the incidents. Some of the children had more than 1 cause of IA intervention. Some of the children had more than 1 cause of IA. Using the experience in the present study, we were able to demonstrate that individualized ICD programming, such as higher VT detection rates, detection restricted to the VF zone and longer detection intervals, was probably crucial to keeping the rate of IAs low.^{10,24,32}

There is more and more evidence that defibrillator shocks can cause myocardial damage, and the shocks have

been associated with increased mortality.^{5,33} In the pediatric population, reductions in the number of IA and the associated significant reductions in total IA energy delivered to the myocardium may have resulted in diminished myocardial damage and lower mortality in this particular group of patients. The time period prior to the 1st intervention (AI or IA) was 350 days (range: 6–2,412 days); and it did not correlate with any other of the factors studied; in particular, it was not an independent variable of SCD/SCA.

There were 3 deaths during the present study, all of them in the pioneer era of ICD implantation in children, and detailed subgroup analyses of the relationship between device programming and death have limited power. The findings from randomized trials and our own experience support the ongoing evolution of ICD therapy for primary prevention, in parallel with programming approaches reducing inappropriate therapies and increasing survival among patients with ICDs.^{10,24}

ICD-system-related complications and actions taken to solve them

In 1980, Mirowski published an article about the use of ICDs in patients who had undergone successful resuscitation.³⁴ The external cardioverter-defibrillator had been a recognized therapeutic tool for decades, but Mirowski was the first to introduce a fully automatic implantable device, comparable to implantable pacemakers.

The 1st report of ICD implantation in a young patient was published in 1988 by Kral et al.¹⁴ The 1st ICD implantation in a teenager in our center was performed in 2000. In that young teenager with CPVT, we initially programmed the VF detection rate at 240 bpm and the detection counter at 24 out of 32; the VT zone was from 200 bpm. Unfortunately, despite optimal pharmacotherapy, therapy-resistant VF occurred. Because of the recurrent VF, despite repeated shocks, we decided to delay the therapy, switching the detection counter to 75 out of 100. That was meant to reduce the number of shocks and thus to reduce adrenergic stimulation, which may be effective in some patients. Nonetheless, the arrhythmia could not be suppressed in any way, and the patient died. Since that time, we have programmed the detection counter to 75 out of 100 in all 3 of our subsequent patients with CPVT. None of them experienced electrical storms during their follow-up periods (which lasted 13, 12 and 10 years, respectively). One of them, who is subject to regular cardiological follow-up every 6–12 months, now has a five-year old daughter.

Lead-related complications are the most common adverse events during follow-up.^{8,10,27} Lewandowski et al. reported a 21% rate of complications requiring surgical intervention.²⁶ In our study, considering all 23 IA (18.2%), more than half of them took place because of LF (17/23; 74%). Despite the significant technological progress that has been made in recent years in the field, ICD implantation is still

more complicated in children than in adults.^{8,9,35–38} There are no dedicated leads for small vessel diameters. Existing ICD devices are not adapted to the small body surface and weight of a pediatric patient, and abdominal implantation of the power generator may be necessary.^{20,28,29,39,40} Lead failure is an important issue to all physicians taking care of patients with ICDs because of its serious consequences. Unfortunately, its incidence is difficult to determine, due to several factors. During the past 2 decades, several recalled leads have appeared on the market.³⁷ The recalled Medtronic Sprint Fidelis series serves as an example of conductor and insulation failure. Recently, there was a recall of SJM devices. According to data from the literature, the failure rate for Sprint Fidelis leads is about 20% at 10 years. Our management of children with functioning recalled leads was very individual. In all cases, we focused on intensifying the monitoring plan, and followed the programming strategy recommended by the manufacturer.³⁷ In cases of patients with externalized cables, but with no electrical abnormalities, we reprogrammed the devices, and performed extraction with the insertion of a new ICD lead during a planned device exchange. Since 2010 lead extraction has been performed at our center with surgical backup.

Study limitations

This study has several limitations. The study design was a retrospective cohort analysis, and underestimation of LF cannot be excluded. The indications for ICD implantation are more heterogenic than in an adult population, where ischemic origins predominate. The programming details of anti-tachycardia therapy could not be systematically assessed, as it was very heterogeneous over the long study period and frequently changed even in the same individual. Patients presenting with abnormal lead parameters underwent standard radiography to assess whether any structural damage was present. The exact mechanisms of LF could not be confirmed in every case. Based on clinical decisions whether to extract or abandon the lead, not all the leads were visually examined, and were not available for a returned product analysis by the manufacturer.

Conclusions

The ICD implantation indications in children are more heterogeneous than in the adult population. In the pediatric population undergoing ICD implantation, the treatment strategy is influenced by gender. The rate of IAs in our group of pediatric patients was low. Rigorous pharmacotherapy and individual ICD programming seemed to be of paramount importance. Lead malfunctions were the most prevalent complications observed, and most of them were related to Sprint Fidelis leads.

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