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Radiofrequency Catheter Ablation of Right Ventricular Outflow Tachycardia in Children and Adolescents

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Objectives. **The current study reviews the safety and efficacy of radiofrequency catheter ablation for the treatment of right ventricular outflow tachycardia in children and adolescents and describes a modified method for mapping the tachycardia focus.**

Background. **Although radiofrequency catheter ablation has proved highly effective for the treatment of supraventricular tachycardia during childhood and adolescence, its application in children with idiopathic right ventricular outflow tachycardia has been limited.**

Methods. **Six children (mean [±SD] age 10.6 ± 2.4 years, range 6 to 16) with right ventricular outflow tachycardia underwent seven radiofrequency catheter ablation procedures. The mean tachycardia cycle length was 323 ± 24 ms (range 300 to 360). Two multipolar catheters were positioned in the right ventricular outflow tract to map the tachycardia focus.**

Results. **Radiofrequency catheter ablation was successful in five (83%) of the six children (95% confidence interval 36% to 99%). At successful ablation sites, local endocardial activation times preceded the surface QRS onset by 46 ± 5 ms (range 37 to 57), and there was concordance of the 12-lead pace map and the electrocardiogram (ECG) in 11 (one patient) to 12 ECG leads (four patients). One patient developed complete right bundle branch block during radiofrequency catheter ablation. There were no additional complications and no clinical recurrences over a mean follow-up period of 12.7 ± 3.8 months (range 9 to 22).**

Conclusions. **These results suggest that radiofrequency catheter ablation is a safe and effective treatment for right ventricular outflow tachycardia during childhood and adolescence. In addition, tachycardia mapping may be enhanced by use of a multipolar right ventricular outflow catheter technique.**

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Radiofrequency catheter ablation has proved highly effective for the treatment of idiopathic right ventricular outflow tachycardia in adult patients (1–5). Although radiofrequency catheter ablation has become a highly accepted mode of therapy for supraventricular tachycardia during childhood (6–9), its application in children and adolescents with right ventricular outflow tachycardia has been limited. The purpose of the current study, therefore, was to 1) assess the safety and efficacy of radiofrequency catheter ablation for the treatment of right ventricular outflow tachycardia, and 2) describe a modified method for mapping the right ventricular outflow tachycardia focus in children and adolescents.

Methods

Patient characteristics. The study included six consecutive patients with recurrent idiopathic monomorphic right ventricular outflow tachycardia who underwent attempts at catheter-guided ablation (mean [±SD] age 10.6 ± 2.4 years, range 6 to 16; four male, two female) (Table 1). Presenting symptoms included palpitations and chest pain in two patients; the remaining four were asymptomatic. One patient had a family history remarkable for sudden death in a paternal uncle during the second decade of life. Three patients were taking antiarrhythmic medications (atenolol [Tenormin], 0.4 mg/kg body weight per day; propranolol [Inderal], 1.8 mg/kg per day; atenolol, 0.9 mg/kg per day plus mexiletine, 6 mg/kg per day, respectively) initiated at the referring institution.

Ventricular tachycardia manifested a left bundle branch configuration with an inferior QRS axis in all six patients (mean cycle length 323 ± 24 ms, range 300 to 360). Tachycardia was nonsustained in two patients, incessant and nonsustained in one and sustained in three. All six patients had normal structural cardiac anatomy and function by two-dimensional echocardiography and cardiac magnetic resonance imaging (MRI). Bruce protocol exercise study initiated sustained ventricular tachycardia in all six patients. Right heart catheterization (five patients) and right ventricular cineangiography (four patients) results were normal. No histologic abnormalities were found in two patients who underwent right ventricular endomyocardial biopsy.

Electrophysiologic study. Electrophysiologic study was performed at least 72 h after discontinuation of antiarrhythmic medications. Written informed consent was obtained from the parents or guardian of each patient under an institutional

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Table 1. Summary of Patient Characteristics

Pt No.	Age (yr)/ Gender	Tachycardia CL (ms)	Antiarrhythmic Medications	Mode of Induction	Outcome	No. of RFCA Lesions	Power Output (W)	Pace Map (no. of leads)	Tachycardia Mechanism	Tachycardia Focus	Activation Time (ms)*
1	12/F	330	None	Isoproterenol	Successful repeat ablation†	4	35	12/12	Automaticity	Anteroseptal	−32
2	16/F	320	Atenolol, mexiletine	Ventricular burst pacing during isoproterenol infusion	Success	12	45	12/12	Triggered activity	Posteroseptal	−57
3	9.5/M	300	Propranolol	Ventricular burst pacing during isoproterenol infusion	Success	16	45	12/12	Triggered activity	Posteroseptal	−45
4	10/M	330	None	Isoproterenol	Success	30	55	11/12	Automaticity	Anterolateral	−43
5	6/M	360	None	Isoproterenol	Success	51	50	12/12	Automaticity	Anterolateral	−37
6	10/M	350	Atenolol	Isoproterenol	Failure	4	30	8/12	Automaticity	Possible septal (subepicardial)	‡

*Negative values for activation time refer to time interval preceding onset of surface QRS complex. †Initial ablation failure/successful repeat ablation (data presented are from second ablation session). ‡No successful radiofrequency energy application. CL = cycle length; F = female; M = male; Pt = patient; RFCA = radiofrequency catheter ablation.

review board protocol before the study. Catheterization was performed under general anesthesia with assisted ventilation (two patients) or under conscious sedation with ketamine and valium (four patients). Electrophysiologic catheters were placed by femoral venous access. A 6F tripolar catheter was placed in the His bundle position; a 5F quadripolar catheter was positioned in the right ventricular apex; and two multipolar catheters (6F dodecapolar catheter [USCI] and 7F deflectable-tip octapolar catheter [EP Technologies, Inc.]) were positioned in the right ventricular outflow tract. The multipolar catheters were positioned to intersect in the right ventricular outflow tract, with one catheter relatively parallel to, and the other perpendicular to, the sagittal plane of the outflow tract. Electrocardiographic leads I, aVF, V_1, and V_6 were recorded along with intracardiac electrograms by a Midas System 2500 (E for M Corp.) electrophysiologic recording system.

Right ventricular pacing was performed at baseline using a stimulus duration of 2 ms and a current strength at twice the diastolic threshold. After baseline programmed ventricular pacing, an isoproterenol infusion (0.025 to 0.05 $\mu g/kg$ per min) was titrated to sustain a 30% increase in the basal heart rate. If the isoproterenol infusion did not initiate ventricular tachycardia, programmed ventricular pacing was repeated during the infusion. *Nonsustained tachycardia* = tachycardia lasting 6 beats to 30 s in duration; *sustained tachycardia* = tachycardia lasting ≥30 s in duration; *incessant tachycardia* = recurrent sustained episodes of tachycardia constituting >20% of the total Holter sampling interval.

Although precise determination of the tachycardia mechanism at electrophysiologic study alone is not completely feasible, we attempted to characterize the mechanism of tachycardia as outlined by Calkins et al. (3): *abnormal automaticity* = tachycardia that was initiated spontaneously during isoproterenol infusion; and *triggered activity* = tachycardia reproducibly initiated over a narrow range of ventricular paced cycle lengths with or without isoproterenol infusion.

Tachycardia mapping. On the basis of tachycardia configuration (left bundle branch block pattern with an inferior QRS axis), mapping was concentrated in the right ventricular outflow tract. Earliest endocardial activation times were isolated to a specific quadrant of the right ventricular outflow tract using two multipolar catheters. The catheters were positioned in the right ventricle so as to intersect proximally (Fig. 1) and were positioned first in an anterior then a posterior plane. In each plane, local endocardial activation times were measured relative to the onset of the surface QRS complex during tachycardia. The catheters were then repositioned to intersect at the point of earliest local endocardial activation in the appropriate anteroposterior plane. A large-tipped deflectable quadripolar catheter was then used to perform detailed mapping in the right ventricular outflow quadrant that demonstrated the earliest endocardial times (Fig. 2). Pace maps were recorded at each site during sinus rhythm with right ventricular pacing at a cycle length equal to the tachycardia cycle length, or during tachycardia at a cycle length less than the tachycardia cycle length. In the latter instance, pace mapping was per-

Figure 1. Anteroposterior (**left**) and lateral (**right**) cineradiographs illustrating the two multipolar catheters positioned in the right ventricular outflow tract. A quadripolar catheter is positioned in the right ventricular apex, and a large-tipped deflectable quadripolar ablation catheter is positioned at the intersection of the two multipolar catheters.

formed at two different cycle lengths to rule out progressive fusion suggestive of entrainment. The QRS configuration in each of the 12 ECG leads was compared with that recorded during the clinical tachycardia.

Radiofrequency catheter ablation. Radiofrequency energy was delivered at endocardial sites that demonstrated both 1) early activation times relative to the surface QRS and the right ventricular outflow electrograms, and 2) a high concordance between the 12-lead ECG during tachycardia and the 12-lead pace map. A 7F catheter with either a 4-mm (Medtronic-Cardiorhythm) (four patients) or 6-mm distal tip (EP Technologies) (two patients) or an 8F catheter with an 8-mm distal tip (EP Technologies) (one patient) was used for energy delivery. Energy outputs of 30 to 45 W were applied for 20 to 120 s between the distal electrode of the quadripolar catheter and a large-surface area, indifferent skin electrode positioned over the left scapula. The energy source for ablation (Radionics RFG-3B) delivered a continuous unmodulated waveform at 500 kHz. Energy delivery was discontinued if an abrupt impedance increase occurred or if energy delivery failed to interrupt the tachycardia within 30 s after application. If tachycardia ceased during the initial 30 s of radiofrequency energy application, energy delivery was continued for a total of 60 to 120 s. An additional one to three radiofrequency energy applications were delivered at the successful ablation site or at an immediately adjacent site for an additional 60 s. Intravenous heparin (150 U/kg) was administered before the initial radiofrequency energy application, and subsequent heparin boluses were administered throughout the remainder of the procedure to maintain activated clotting time >300 s.

Patients were observed in the electrophysiology laboratory for 1 h after the successful energy applications. During this interval, ventricular pacing protocols were repeated at baseline and during isoproterenol infusion. The procedure was considered successful if no spontaneous or induced ventricular ectopic activity, similar in configuration to the clinical arrhythmia, were observed during this interval.

Follow-up. All patients underwent ECG monitoring by continuous telemetry display during the postablation hospital course. Two-dimensional echocardiograms were obtained in

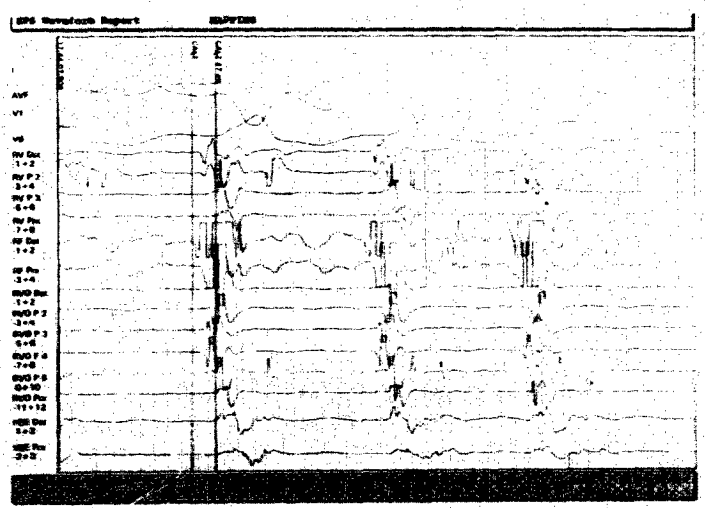

Figure 2. Surface electrocardiogram leads I, aVF, V_1 and V_6 and local ventricular electrograms during tachycardia recorded (from top to bottom) from the right ventricular octapolar catheter (RV 1 to 8), the radiofrequency ablation catheter (RF 1 to 4), the right ventricular decapolar catheter (RVO 1 to 10) and the His bundle catheter (HBE 1 to 3). Endocardial activation in the distal electrode pair (P) of the radiofrequency catheter (RF Dst) precedes the surface QRS onset by 47 ms. Prx = proximal.

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the catheterization laboratory at the completion of the procedure and 1 day after ablation. In addition, 12-lead and signal-averaged ECGs were recorded, and continuous Holter monitoring was performed before hospital discharge. Aspirin therapy was instituted (81 to 324 mg every other day) for a total of 6 days (three doses) after ablation, independent of procedural outcome.

At 1, 3, 6 and 12 months after ablation, a complete history was obtained, and clinical examination, 12-lead electrocardiography and 24-h ambulatory Holter monitoring were performed in each patient. A Bruce protocol exercise treadmill study was performed 6 to 12 weeks after ablation in all patients.

Statistical analysis. Continuous variables are expressed as mean value ± 1 SD. *Successful outcome* was defined as the absence of clinically similar ventricular ectopic activity by noninvasive monitoring before hospital discharge. Endocardial activation times and 12-lead pace maps at successful versus unsuccessful ablation sites were compared by analysis of variance. Power output during successful and unsuccessful energy applications was compared by a Fisher exact test. Statistical significance was accepted at $p < 0.05$.

Results

Six patients underwent a total of seven radiofrequency ablation sessions. A repeat procedure was successful 5 weeks after unsuccessful ablation attempts in one patient (Patient 1, Table 1). Overall, radiofrequency catheter ablation successfully eliminated tachycardia in five (83%) of the six children (95% confidence interval 36% to 99%).

Tachycardia mechanism. At electrophysiologic study, monomorphic ventricular ectopic activity identical in configuration to the clinical arrhythmia was present at baseline or was induced in all patients. Isoproterenol infusion initiated single ventricular premature beats at initial study and nonsustained tachycardia during the subsequent study in one patient (Patient 1, Table 1), bigeminy in one and sustained tachycardia in two. In the remaining two children, burst pacing during isoproterenol infusion induced nonsustained tachycardia. On the basis of these findings, the mechanism of tachycardia was thought to be abnormal automaticity in four patients and triggered activity in two.

Mapping. Endocardial activation times at successful ablation sites preceded the surface QRS onset by a mean of 46 ± 5 ms (range 37 to 57 ms) compared with 28 ± 7 ms (range 5 to 38 ms) at unsuccessful sites ($p = 0.04$) (Fig. 2). The earliest endocardial activation times were recorded at sites demonstrating the highest correlation between the pace map and the 12-lead ECG, which is consistent with the findings of Morady et al. (10). The 12-lead pace map demonstrated concordance with the clinical tachycardia in 11 (one patient) to 12 (four patients) ECG leads at successful ablation sites (Fig. 3). In the one patient with unsuccessful ablation, neither early local endocardial activation times nor a representative pace map could be recorded at any right or left ventricular endocardial site.

Radiofrequency catheter ablation. The mean delivered power during successful catheter ablation was 43 ± 4 W (range 30 to 45), and the mean duration of radiofrequency energy application before loss of the marker arrhythmia was 7.6 ± 3.5 s (range 3 to 15). The mean number of radiofrequency energy applications/procedure was 23 ± 15 (range 4 to 51), and the mean fluoroscopy time was 22 ± 8.3 min (range 10 to 39).

Radiofrequency catheter ablation was unsuccessful in one patient (Patient 1, Table 1) with an anteroseptal tachycardia focus. In this patient the initial procedure was performed under general anesthesia with assisted ventilation. Although the clinical tachycardia was sustained, only rare, single ventricular depolarizations could be induced at catheterization. The inability to sustain tachycardia compromised tachycardia mapping and the assessment of ablation effect. At repeat study using conscious sedation, sustained tachycardia was easily inducible, and the tachycardia focus was successfully mapped and ablated. In another patient (Patient 6, Table 1), exhaustive mapping efforts were unsuccessful in isolating early endocardial activation times or a representative pace map. As a result, only a limited number of energy applications were delivered in this patient, and ablation attempts were unsuccessful.

Tachycardia focus. The anatomic location of the tachycardia focus was determined from anteroposterior and lateral right ventricular digital cineradiographs. The right ventricular outflow was divided into septal and lateral anterior and posterior regions, similar to those described by Coggins et al. (11). The tachycardia focus was anteroseptal in two patients, anterolateral in one and posteroseptal in two (Fig. 4).

Tachycardia manifested an initial low amplitude negative deflection (q wave) in surface lead I in the two patients with an anteroseptal tachycardia focus and a small r wave in surface lead I and precordial lead V_1 in the two patients with a posteroseptal tachycardia focus. In the one patient with unsuccessful mapping and ablation attempts (Patient 6, Table 1), the surface ECG manifested a deep q wave in lead I, possibly indicating that the tachycardia arose deep within the interventricular septum. Ablation attempts through both right and left ventricular approaches failed to interrupt tachycardia in this patient.

Complications. Complete right bundle branch block occurred during ablation of an anteroseptal tachycardia focus in one patient. There were no additional complications, and 12-lead and signal-averaged ECGs in the five remaining patients were unchanged. No patient had any echocardiographic evidence of right ventricular dyskenesia, pulmonary insufficiency or pericardial effusion.

Follow-up. All patients were followed up for a mean of 12.7 ± 3.8 months (range 9 to 22) after ablation. During this interval, no patient experienced symptoms of tachycardia, and no patient demonstrated ectopic activity by ambulatory Holter monitoring. Exercise treadmill study performed a mean of 6.8 ± 2.3 weeks after ablation failed to induce ventricular ectopic activity in any successfully treated patient.

Discussion

Major findings. The current study documents the safety and efficacy of radiofrequency catheter ablation for the treat-

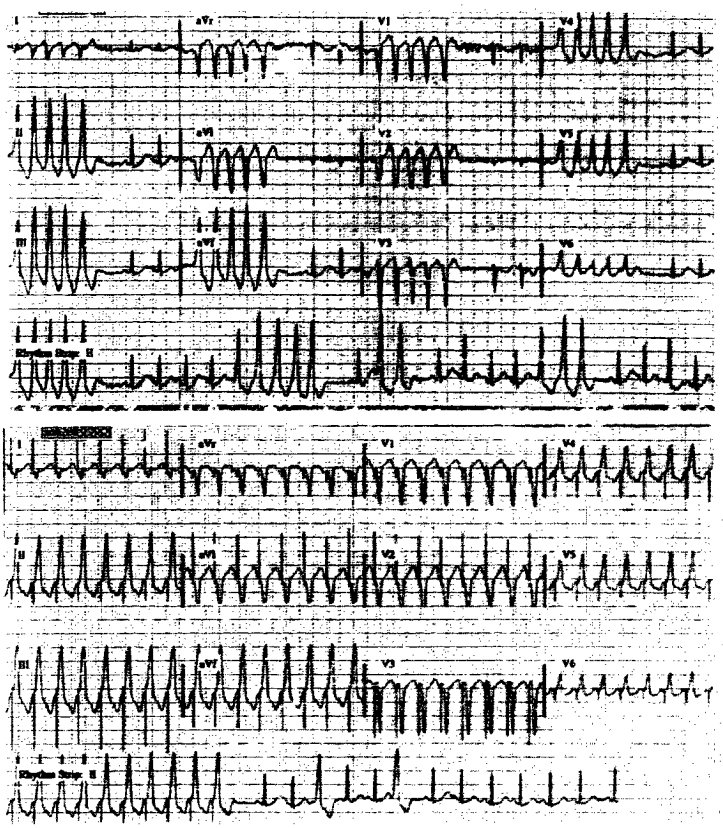

Figure 3. Top, Twelve-lead electrocardiogram (ECG) during nonsustained tachycardia in a 10-year old patient with an anteroseptal tachycardia focus. **Bottom,** Twelve-lead pace map during bipolar pacing performed at the successful anteroseptal radiofrequency ablation site in the same patient. There is concordance of the ECG (**top**) and the pace map (**bottom**) in all 12 ECG leads.

ment of right ventricular outflow tachycardia in a select pediatric cohort. There were no major complications and no recurrences over a mean follow-up period of 12.7 ± 3.8 months. Despite the relatively brief follow-up period, the complete absence of tachycardia relative to the frequency of the presenting arrhythmia suggests a high likelihood of permanent cure.

Predictors of successful outcome. In the present study early endocardial activation times and a highly concordant 12-lead pace map were strong predictors of ablation success. Early loss of the marker arrhythmia may also be predictive of ablation success, but this possibility was not specifically analyzed in the current study. The early loss of the marker arrhythmia during successful ablation suggests that prolonged energy applications are unlikely to alter ablation outcome and are unwarranted in the absence of early ablation effect.

One important criterion for ablation success is the ability to easily induce sustained tachycardia during the procedure. As evidenced in the current study, and as suggested by Walsh et al. (12) in patients with focal atrial tachycardias, deep sedation such as that provided by general anesthesia can suppress the tachycardia focus and therefore should be avoided during catheterization in such patients.

Modified mapping technique. The mapping technique used in the current study provides a method of isolating early endocardial activation to a specific right ventricular outflow quadrant where detailed mapping may be concentrated. The catheters also provide a reference similar to that provided by the coronary sinus catheter in mapping left-sided accessory pathways. A limitation of the technique lies in the application of a single-plane mapping reference to the right ventricular outflow, a three-dimensional structure. Thus, if the catheters are positioned anteriorly in the outflow tract and the tachycardia focus lies in a posterior plane, the technique might confound mapping and prolong the procedure (Patient 5, Table 1). This problem was overcome in the latter stages of the current study by using biplane cineradiography to position the catheters first anteriorly then posteriorly in the right ventricular outflow. Mapping was then performed in the appropriate anteroposterior plane. As suggested by the current study, the ECG may also provide some insight into the anatomic location of the tachycardia focus.

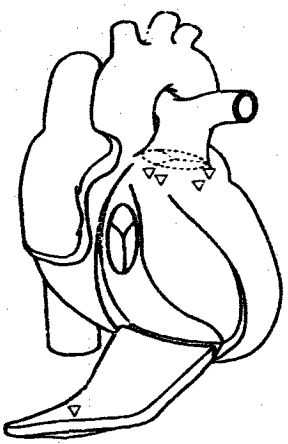

Figure 4. Schematic of right ventricle. **Open triangles** = successful radiofrequency ablation sites.

Indications for therapy. The indications for radiofrequency catheter ablation in children with right ventricular outflow tachycardia remain to be clearly determined. At our center radiofrequency catheter ablation is considered only for patients with a single tachycardia focus and with no evidence of right ventricular myopathy or degenerative right ventricular changes by echocardiography, cineangiography, signal-averaged electrocardiography or cardiac MRI. Diffuse right ventricular changes or multiple tachycardia foci suggest a global process (13); therefore, ablation therapy was not considered in such patients. In patients with a discrete focus of tachycardia, our indications for therapy include incessant sustained tachycardia, tachycardia associated with syncope or presyncope and sustained tachycardia during catecholamine stress. Therapeutic options include pharmacotherapy or catheter-guided therapy. We have identified syncope and presyncope as indications for radiofrequency catheter ablation and have also offered this therapy to patients in whom medical therapy is undesirable. We believe radiofrequency catheter ablation to be a reasonable and safe option to prolonged medical therapy in patients with right ventricular outflow tract tachycardia.

Study limitations. The lack of complications in the current study does not rule out potential serious procedure-related complications, especially given the small number of study patients. Clearly, the complications documented during radiofrequency ablation of right ventricular outflow tachycardia in adults (1,3,11) apply to pediatric patients. To our knowledge, the current study represents the first report of radiofrequency catheter ablation of right ventricular outflow tachycardia in pediatric patients and suggests that the risk for serious complications is likely to be no greater than that reported in adults.

In the present study, endocardial activation times and the 12-lead pace map were both used in mapping the tachycardia focus. Thus, which technique provides more accurate mapping could not be determined.

Finally, 12-lead pace mapping was performed by bipolar pacing utilizing the distal electrode pair of the ablation catheter. Unipolar pacing may provide more precise information regarding the location of the tachycardia focus, similar to that suggested by Walsh et al. (12) for mapping focal atrial tachycardias.

Conclusions. Our results suggest that radiofrequency catheter ablation is a safe and effective option for the treatment of children and adolescents with right ventricular outflow tachycardia. However, the late effects of radiofrequency energy application in the human ventricle remain to be determined. Research involving radiofrequency lesions delivered in the ventricles of infant lambs has suggested that these lesions enlarge over time (14). Therefore, the safety of radiofrequency catheter ablation of right ventricular outflow tachycardia in very young children remains to be determined and may carry a higher long-term risk.

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