Pacing the Human Cardiac Conduction System During Open-heart Surgery

By Joel Kupersmith, M.D., Ehud Krongrad, M.D., Frederick O. Bowman, Jr., M.D., James R. Malm, M.D., and Albert L. Waldo, M.D.

SUMMARY

Specialized fiber electrograms were recorded from selected sites along the His bundle and bundle branches during open-heart surgery in 26 patients. The heart was then paced from the same recording sites. Stimuli applied to the proximal His bundle recording site always resulted in His bundle pacing, which was characterized by a stimulus artifact-to-QRS interval which equaled or very nearly equaled the previously recorded His bundle electrogram-to-QRS interval, and no change in QRS duration or waveform from that recorded with a conducted atrial beat. When stimuli were applied to distal His bundle recording sites, the response was variable: in some instances, ventricular pacing occurred; in other instances, His bundle pacing occurred; and in still other instances, ventricular pacing occurred when high stimulus amplitudes were applied, while His bundle pacing occurred when the stimulus amplitudes were reduced below a range of 0.5–3.5 ma. Stimuli applied to the right or left bundle branch recording sites always resulted in ventricular pacing. Therefore, when stimuli are applied to specialized fiber recording sites and His bundle pacing results, it is certain that the site of the previously recorded specialized fiber electrogram is the His bundle, but when ventricular pacing results, the site of origin of the previously recorded specialized fiber electrogram could be the distal His bundle or the bundle branches.

Additional Indexing Words:
His bundle electrogram  Left bundle branch electrogram  Right bundle branch electrogram
Catheter electrodes Ventricular pacing His bundle pacing
Specialized fiber electrogram Atrial electrogram Ventricular electrogram
Electrode probe

WHEN USING THE CARDIAC CATHETER electrode technique for recording electrograms from the His bundle and bundle branches, it is difficult to accurately localize the site of origin of recorded specialized fiber electrograms. Among the methods used to localize specialized fiber electrograms are fluoroscopic visualization of the recording electrode during cardiac catheterization and extrapolation of anatomic location from specialized fiber electrogram-to-QRS intervals. The inexact nature of fluoroscopic visualization, the problems of overlap in the range of normal intervals from different recording sites, and the difficulty in evaluating abnormal intervals have been discussed elsewhere. Many investigators have utilized the technique of pacing the heart from the specialized fiber recording site to help determine the site of origin of the specialized fiber electrogram. In this study, stimuli were applied to His bundle and bundle branch recording sites under direct visualization of the heart during open-heart surgery in order to determine if this technique is of value in localizing His bundle and bundle branch electrograms.

Methods

Twenty-six patients, aged three years, one month, to 62 years, were studied during cardiopulmonary bypass initiated in the course of open-heart surgery. The experimental protocol varied somewhat for each patient and was determined by the nature and requirements of the surgical procedure. Informed consent was obtained from all patients. A summary of pertinent data on the patients studied is provided in table 1. During periods of data collection, body temperature measured from the retrocardiac portion of the esophagus or from the rectum was 32–37°C. There were no

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conduction abnormalities in the preoperative ECG of any patient. In 23 of the patients, studies were performed during a normally conducted atrial rhythm. In the other three patients (cases 23, 24 and 25, table 1) studies were performed shortly after termination of ischemic arrest induced by cross-clamping of the aorta. The ischemic arrest in these three patients resulted in depressed cardiac conduction which in turn resulted in a prolonged His bundle electrogram-to-QRS interval and a prolonged QRS duration. Since depression of conduction was present both before and after pacing at specialized fiber recording sites, it did not interfe with evaluation of the results. All patients received small amounts of atropine and morphine or demerol approximately three hours prior to surgery and halothane or morphine anesthesia during surgery.

Electrophysiologic studies were performed using previously described techniques. Bipolar silver electrodes were placed in the region of the sinus node of each patient to record atrial activity and to permit bipolar atrial pacing. A probe containing three silver electrodes 1–2 mm apart was used either for bipolar pacing or for recording bipolar electrograms from the proximal His bundle, the distal His bun-

### Table 1

Clinical Information and Data on the 26 Patients Studied

<table>
<thead>
<tr>
<th>Case</th>
<th>Age*</th>
<th>Diagnosis</th>
<th>Temp. during study (°C)</th>
<th>Proximal His bundle pH-Q (msec)</th>
<th>S-Q§ threshold (ms)</th>
<th>HB threshold‡ (ms)</th>
<th>Distal His bundle dH-Q (msec)</th>
<th>S-Q§ threshold (ms)</th>
<th>HB threshold‡ (ms)</th>
<th>Right, bundle branch RB-Q (msec)</th>
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</table>

*Age is given to the nearest month for patients below age 15 years and to the nearest year for patients 15 years of age and older.

†Stimulus artifact-to-QRS interval during pacing of the proximal His bundle recording site.

‡Threshold stimuli for His bundle pacing at the proximal His bundle recording site.

§Stimulus artifact-to-QRS interval for those patients in whom stimulation of the distal His bundle recording site resulted in selective His bundle pacing.

Abbreviations: abs PV = absent pulmonary valve; AR = aortic regurgitation; AS = aortic stenosis; 2° ASD = atrial septal defect, ostium secundum type; dH-Q = distal His bundle to QRS interval; HB = His bundle; LB-Q = left bundle branch-to-QRS interval; MR = mitral regurgitation; PAPVD = partial anomalous pulmonary venous drainage; pH-Q = proximal His bundle-to-QRS interval; PS = pulmonary stenosis; RB-Q = right bundle branch-to-QRS interval; S-Q = stimulus artifact-to-QRS interval; T/F = Tetralogy of Fallot; VA = ventricular aneurysm; VSD = ventricular septal defect.
PACING THE HUMAN A-V CONDUCTION SYSTEM

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Pacing the Right or Left

A electrode was then moved by increments of 5 mm (i.e., the probe diameter) medially along the interatrial septum toward the membranous septum. The first appearance of a specialized fiber electrogram in the record identified the proximal His bundle. 1, 17 Electrograms recorded from the specialized conduction system at the membranous septum identified the distal His bundle. For studies on the left heart, the probe electrode was initially placed on the membranous septum. Electrograms recorded from the specialized conduction system distal to the membranous septum in the right ventricle were labeled right bundle branch and those in the left ventricle were labeled left bundle branch.

At each site, after electrograms had been recorded, stimuli were applied via the same bipolar electrodes. The stimulus amplitude was varied to determine the threshold for pacing the specialized conduction system (i.e., the minimum current delivered through the probe electrode that was needed to pace the specialized conduction system) and to determine the effects of stimulus strength of up to 10 ma on the waveform and duration of the QRS complex and on the interval from the stimulus to the onset of ventricular activation.

All leads in contact with the heart were isolated from ground and from the recording apparatus by isolation transformers. The electrograms and ECGs were monitored simultaneously on a DR-12 Electronics for Medicine switched beam oscilloscope and recorded on photographic paper moving at 100 mm/sec. ECGs calibrated at 2 cm/mV were recorded between filter frequencies of 0.1-500 Hz and the electrograms were recorded between 12-500 Hz. All stimuli were provided by a Medtronic 1187 Special Digital Threshold Stimulator and delivered through a stimulus isolator.

During the conducted atrial rhythm, the interval from the intrinsic deflection of the His bundle or bundle branch electrogram to the onset of the earliest QRS complex was measured. During stimulation of the specialized fiber recording site, the interval from the onset of the stimulus artifact to the onset of the QRS complex, the QRS duration, and the interval from the stimulus artifact to the intrinsic deflection of the atrial electrogram were measured (table 1). A vernier measuring device with an accuracy of ± 1 msec at the recorded paper speed was used for all measurements.

Results

Studies on the Right Heart

Proximal His Bundle Recording Site. Stimuli were applied to the proximal His bundle recording site in nine patients (table 1). A representative record is shown in figure 1. Panel A of figure 1 illustrates a proximal His bundle electrogram recorded during a conducted atrial rhythm produced by atrial pacing. The top trace shows the electrogram recorded from the proximal His bundle. The second trace shows the stimulus artifact delivered through the atrial electrodes during the paced atrial rhythm, and the bottom three traces show ECG leads aVR, aVL, and aVF. The proximal His bundle electrogram-to-QRS interval was 50 msec. Panel B shows the results of pacing from the proximal His bundle recording in this patient. The top trace shows an atrial electrogram recorded through the same electrodes used for atrial pacing in panel A; the bottom three traces again show ECG leads aVR, aVL, and aVF. Note that the characteristic features of His bundle pacing are demonstrated in figure 1B: the stimulus artifact-to-QRS interval in the ECG equals or nearly equals the previously recorded His bundle-to-QRS interval (50 msec), and there is no change in QRS duration or waveform from the ECGs of the conducted atrial rhythm (panel A, bottom 3 traces). His bundle pacing with these characteristics occurred in all nine patients in whom stimuli were applied to the proximal His bundle recording site. Pacing thresholds for the proximal His bundle ranged from 0.1 to 3.5 ma (table 1).

In addition, by recording an atrial electrogram during stimulation of the proximal His bundle recording site, it was possible to determine whether there was selective proximal His bundle pacing or whether there was simultaneous pacing of the His bundle and atrium. When the proximal His bundle was selectively

![Figure 1](http://circ.ahajournals.org/)

**Figure 1**

Representative example of His bundle pacing which resulted from stimuli applied to the proximal His bundle recording site in case 3. A) Records obtained during a conducted atrial rhythm produced by atrial pacing. Intervals: proximal His bundle electrogram-to-QRS (pH-Q) = 50 msec; QRS = 55 msec. B) Records obtained during proximal His bundle pacing. Note that the stimulus artifact-to-QRS interval (S-Q) (50 msec) equals the pH-Q interval in panel A and the QRS duration (QRS) (85 msec) and waveform are the same as in panel A. Also, the stimulus artifact-to-atrial electrogram interval (S-A) is 119 msec, consistent with selective pacing of the His bundle. A = stimulus delivered through atrial bipolar electrodes (panel A) or atrial electrogram (panel B); HB = His bundle electrogram; R, L, F = standard ECG leads aVR, aVL, and aVF respectively; S = stimulus artifact.

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paced, conduction of the impulse to the atrial recording site proceeded retrograde from the His bundle, through the A-V node to the atrium. Thus the interval between the stimulus artifact and atrial electrogram was relatively long, a finding consistent with the expected conduction delay in the A-V node or there was retrograde His bundle-atrial block. When the His bundle and atria were simultaneously paced, conduction of the retrograde impulse to the atrial recording site proceeded only through the right atrium and the interval between the stimulus artifact and the atrial electrogram was much shorter than it was when the pathway of retrograde conduction included the A-V node. In figure 1B, the interval between the stimulus artifact and the atrial electrogram was 119 msec, a relatively long interval consistent with selective His bundle pacing and retrograde conduction to the atrium through the A-V node. In four of the nine patients in whom stimuli were applied to the proximal His bundle recording site, selective His bundle pacing occurred and in the other five patients, simultaneous atrial-proximal His bundle pacing occurred.

Distal His Bundle Recording Site. Stimuli were applied to the distal His bundle recording site in the right heart of 18 patients. The results of this stimulation were variable and depended in part on stimulus amplitude. Figure 2 shows the results of pacing from the distal His bundle recording site. Figure 2A shows a His bundle electrogram recorded during a conducted atrial rhythm produced by atrial pacing. The distal His bundle-to-QRS interval was 37 msec.

Figure 2B shows a portion of the recordings made during stimulation at the distal His bundle recording site while the stimulus amplitude was gradually reduced from 10 ma. The top trace shows the stimulus artifact delivered through the same electrodes used to record the distal His bundle electrogram shown in panel A; the second trace shows an atrial electrogram recorded from the same electrodes used for atrial pacing in panel A; and the bottom three traces show ECG leads I, II, and III. In the first and second beats, the stimulus amplitude was greater than 3 ma, and right ventricular pacing occurred. Note that during right ventricular pacing, there was no detectable interval between the stimulus artifact and the QRS complex in the ECG leads; there was an increased QRS duration from that recorded during a conducted atrial beat; and the QRS waveform resembled a left bundle branch block pattern. In the third and fourth beats of figure 2B, the stimulus amplitude had been decreased to less than 3 ma, and distal His bundle pacing occurred. During distal His bundle pacing, the stimulus artifact-to-QRS interval (39 msec) (fig. 2B, third and fourth beats) nearly equaled the previously recorded distal His bundle electrogram-to-QRS interval (37 msec) (fig. 2A) and the duration and waveform of the QRS complex in ECG leads I, II, and III were the same as recorded during a conducted atrial beat (panel A).

The results of pacing from the distal His bundle recording site are as follows: in 13 of 18 patients in whom stimuli were applied to the distal His bundle recording site only ventricular pacing occurred; in one of the 18 patients, only distal His bundle pacing occurred; in the remaining four patients, as the stimulus amplitude was gradually decreased from 10 ma, ventricular pacing occurred at higher stimulus amplitudes while distal His bundle pacing occurred when the stimulus amplitude was reduced below a range of from 0.5 to 3.5 ma. Thresholds for distal His bundle pacing ranged from 0.1 to 3.0 ma (table 1). Thus the findings are that in 17 of the 18 patients in whom stimuli were applied to the distal His bundle recording site, ventricular pacing occurred either at all
stimulus amplitudes or over a wide range of stimulus amplitudes. In all these 17 patients, ventricular pacing which resulted from stimulation of the distal His bundle recording site had the ECG characteristics illustrated in the first and second beats of figure 2B, and previously described for right ventricular pacing.\textsuperscript{4, 18, 19} 

One further observation can be made concerning stimulation of the distal His bundle recording site. When ventricular pacing occurred with stimulation of the distal His bundle recording site, it usually was not possible to determine whether selective pacing of the ventricle occurred or whether simultaneous pacing of the ventricle and distal His bundle occurred. It is of interest, however, that in five patients, selective ventricular and simultaneous ventricular-distal His bundle pacing could be distinguished. As mentioned above, in 13 patients, ventricular pacing occurred when both low and high stimulus amplitudes were applied to the same distal His bundle recording site. However, as the stimulus amplitude was reduced from 10 ma, in five of 13 patients an abrupt change occurred in the duration of the QRS complex, or in the interval from the stimulus artifact to the atrial electrogram or in both (fig. 3). Panel A of figure 3 shows a distal His bundle electrogram recorded during a conducted atrial rhythm produced by atrial pacing. Figure 3B shows that ventricular pacing resulted from stimulation of the distal His bundle recording site in this patient. However, when the stimulus amplitude fell below 2 ma, between the second and third beats, an abrupt increase occurred both in the stimulus artifact-to-atrial electrogram interval and in the duration of the QRS complex. The first and second beats of figure 3B represent simultaneous ventricular-distal His bundle pacing while the third and fourth beats represent selective ventricular pacing. With simultaneous ventricular-distal His bundle pacing (first and second beats, fig. 3B), conduction of the retrograde impulse proceeded through the His bundle and the A-V node to the atria. With selective ventricular pacing (third and fourth beats, fig. 3B), the retrograde conduction interval to the atria was longer because the impulse proceeded through ventricular muscle and the bundle branch system as well as the His bundle and A-V node before reaching the atria. Further, with selective ventricular pacing, the duration of the QRS complex was also longer than that with simultaneous ventricular-distal His bundle pacing. The reason for this difference in the QRS duration is that the conducted impulse during simultaneous ventricular-distal His bundle pacing proceeds simultaneously through the rapidly conducting His-Purkinje pathway and the more slowly conducting ventricular muscle, while during selective ventricular pacing, the conducted impulse proceeds for a significant period through ventricular muscle alone. For these reasons, we interpret the change in duration of the QRS complex and stimulus artifact-to-atrial electrogram interval in figure 3B to mean that with decreasing stimulus amplitude, there was a change from simultaneous ventricular-distal His bundle pacing to selective ventricular pacing. In this same manner, we determined that in five patients, simultaneous ventricular-distal His bundle pacing occurred with stimulus amplitudes above a range of 0.5 to 2 ma and selective ventricular pacing occurred with lower stimulus amplitudes.

**Right Bundle Branch Recording Site.** Stimuli were applied to right bundle branch recording sites in seven patients (table 1) and resulted in right ventricular pacing in all seven. Selective right bundle branch pacing never occurred. A representative example of ventricular pacing which occurred during stimulation of the right bundle branch recording site is shown in figure 4. In panel A of figure 4, the top trace shows a right bundle branch electrogram; the second trace shows an atrial electrogram recorded dur-

\[\text{Figure 3}\]

Pacing which resulted from stimulation of the distal His bundle recording site in case 3. This is the same patient in whom the results of pacing the proximal His bundle recording site are shown in figure 1. A) Records obtained during a conducted atrial rhythm produced by atrial pacing. There has been a slight shift in QRS axis during the recording of the distal His bundle electrogram shown here from that obtained during recording of the proximal His bundle electrogram (fig. 1A). Intervals: dH-O = 41 msec; QRS = 86 msec. B) Records obtained while applying stimuli of decreasing amplitude to the distal His bundle recording site. Ventricular pacing occurred in all four beats. In the first and second beats, with stimulus amplitudes above 2 ma delivered to the distal His bundle recording site, simultaneous ventricular-distal His bundle pacing occurred. Between the second and third beats, the stimulus amplitude fell below 2 ma and in the third and fourth beats, selective ventricular pacing occurred. Intervals in the first and second beats: S-A = 145 msec; QRS = 119 msec. Intervals in the third and fourth beats: S-A = 222 msec; QRS = 136 msec. Abbreviations are the same as in figure 2.
which resulted when stimuli were applied to the right bundle branch recording site deserves comment and is illustrated in figure 4B. Here there is an isoelectric interval in lead I between the stimulus artifact and the onset of the QRS complex. Because of this, if only lead I had been recorded, it would have appeared that selective right bundle branch pacing had occurred. However, in the other two recorded ECG leads there was no detectable interval between the stimulus artifact and the onset of the QRS complex, indicating that in fact ventricular pacing had occurred.

Left Heart Studies

Left heart studies were performed in five patients (table 1). Stimuli were applied to the distal His bundle recording site at the membranous septum in the left ventricle in five patients and to left bundle branch recording sites distal to the membranous septum in four patients. The results were similar to those described for pacing of the right heart. Pacing at the distal His bundle recording site resulted in ventricular pacing in another patient; in His bundle pacing in one patient; and in the remaining three patients, ventricular pacing occurred with higher stimulus amplitudes while His bundle pacing occurred when the stimulus amplitudes were reduced below a range of from 1.5–2.5 mA. Thresholds for distal His bundle pacing in the left ventricle ranged from 0.1 to 1.0 mA. Stimuli applied to left bundle branch recording sites in four patients caused ventricular pacing in all four. Neither ECGs suggestive of selective left bundle branch pacing nor ECGs resembling His bundle pacing ever occurred with stimulation of the left bundle branch recording sites. Whenever ventricular pacing resulted from stimuli applied either to the distal His bundle or left bundle branch recording sites in the left ventricle, the QRS waveform resembled a right bundle branch block pattern as has been described previously for human left ventricular pacing.15,16

Discussion

By applying stimuli to the His bundle and bundle branches under direct visualization, we were able to show the characteristics of cardiac pacing from specialized fiber recording sites and the value of this technique in the anatomic localization of specialized fiber electrograms. First, the ECG resulting from His bundle pacing is characterized by a stimulus artifact-QRS interval equal to or nearly equal to the previously recorded His bundle electrogram-QRS interval and no change in the duration or waveform of the QRS complex from that recorded during a conducted atrial beat. Previous studies in the canine heart have described this ECG pattern as characteristic for

Figure 4

Pacing which resulted from stimulation of the right bundle branch recording site in case 16: A) Records obtained during a spontaneous conducted atrial rhythm. Intervals: right bundle branch electrogram-QRS (RB-Q) = 33 msec; QRS = 119 msec. B) Records obtained during pacing of the right bundle branch recording site. Note that ventricular pacing has occurred. Interval: QRS = 153 msec. A = atrial electrogram; I, II, III = standard ECG leads; RB = right bundle branch electrogram.
His bundle pacing\textsuperscript{13-15, 26} and previous studies of pacing from human specialized fiber recording sites using the catheter technique have attributed this ECG pattern exclusively to His bundle pacing\textsuperscript{2, 6, 9-12}. In the present study, this characteristic ECG did in fact occur exclusively when stimuli were applied to the proximal or distal His bundle and never with stimulation of bundle branch recording sites. Therefore, whenever characteristic His bundle pacing occurs with pacing of specialized fiber recording sites, it is almost certain that the site of origin of the previously recorded specialized fiber electrogram is the His bundle. We have used the qualification “almost certain” because it is theoretically possible that stimuli applied to the most proximal portion of the bundle branches may be so rapidly conducted to the other bundle branch that the resulting QRS complex will be identical to that produced by His bundle or atrial pacing. However, evidence for this was not observed in the present study.

ECGs which result from ventricular pacing, on the other hand, were characterized by no detectable stimulus artifact-to-QRS interval and a QRS complex which was increased in duration and was different in waveform from that recorded during a conducted atrial beat. Right ventricular pacing produced ECGs resembling left bundle branch block while left ventricular pacing produced ECGs resembling right bundle branch block. In this study we have shown that ventricular pacing with these general characteristics can result from stimulation either at distal His bundle recording sites or at right or left bundle branch recording sites. It can also result from stimulation of ventricular sites alone. These characteristics of right and left ventricular pacing have been previously reported in humans.\textsuperscript{5, 18, 19} Ventricular pacing which results from stimulation of distal His bundle recording sites thus cannot be distinguished from that which results from stimulation of bundle branch recording sites. Therefore, if ventricular pacing results from stimulation of a specialized fiber recording site, the site of origin of the recorded specialized fiber electrogram could be the distal His bundle or the bundle branches. In this circumstance, it is not possible to distinguish His bundle from bundle branch electrograms by the technique of pacing the heart from the specialized fiber recording site.

Several other observations made in this study can be of help when using the technique of specialized fiber recording site pacing to localize specialized fiber electrograms. First, simultaneous atrial and proximal His bundle pacing occurred in five of nine patients in whom stimuli were applied to the proximal His bundle recording site. Simultaneous atrial excitation never occurred with stimulation of the distal His bundle or bundle branch recording sites, even with stimulus amplitudes up to 10 ma. Thus, if an atrial electrogram is recorded while applying stimuli to the specialized fiber recording site and it is determined that atrial pacing has occurred simultaneously with His bundle pacing, it is likely that the site of stimulation is the proximal His bundle.

Secondly, when the recording and pacing site of the electrodes is the distal His bundle, another observation made in this study may be helpful. In four patients in whom stimuli were applied to the distal His bundle recording site, ventricular pacing occurred with high stimulus amplitude while His bundle pacing occurred when the stimulus amplitude was reduced. Therefore, if ventricular pacing from a specialized fiber recording site occurs, gradual reduction of the stimulus amplitude may result in His bundle pacing, indicating that the recording and pacing site is probably the distal His bundle.

In this regard it is of interest that with the catheter electrode technique, stimulus amplitudes of up to 15 ma are reportedly used to pace the His bundle\textsuperscript{9} while in this study, thresholds for His bundle pacing (i.e., the minimum currents delivered through the probe electrodes that were necessary to pace the His bundle) were far lower, ranging from 0.1 to 3.5 ma. These thresholds suggest that stimuli of amplitudes as high as 15 ma may not be necessary to pace the His bundle in the catheter technique. However, differences in technique may permit smaller stimulus amplitudes to pace the heart in the technique used here, where the electrode probe is directly in contact with the heart, than when using the catheter electrode technique.

There is another possibly important difference between the technique used for this study and the catheter electrode technique. The bipolar electrodes used in the catheter technique often are spaced as widely as 1–2 cm apart while in this study the bipolar electrodes were narrowly spaced, i.e., 1 or 2 mm. With electrodes spaced as widely as 1–2 cm, one of the electrode pairs could be in contact with the His bundle while the other electrode is in contact with the right bundle branch. Moreover, as noted previously, one electrode could be in contact with the atrium while the other is in contact with the His bundle or ventricle. This could cause considerable confusion in localizing the site of origin of the previously recorded specialized fiber electrogram. If a catheter with closely spaced electrodes is used, electrograms can be recorded from and stimuli applied to a more discrete anatomic site, making interpretation of recorded data more reliable. This laboratory\textsuperscript{1} and others\textsuperscript{21} have emphasized the preferability of using catheter electrodes with closely spaced bipolar electrodes, i.e., no more than 1 or 2 mm apart.
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