# Detection of the S3 Gallop in the Emergency Department using the Heart Energy Signature Method

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**ABSTRACT**

Limited tools are available for emergency department clinicians to aid in accurate diagnosis of heart failure. As a result up to 15-20% of emergency department patients are misdiagnosed, resulting in a delay to definitive therapy and increased morbidity and mortality. The S3 heart sound has excellent specificity for heart failure and left ventricular dysfunction, and can be detected instantly during auscultation. However, this is often difficult due to the masking effect of other heart sounds, significant ED background noise, and patient body habitus.

We present a new method of detecting the S3 heart sound using joint time-frequency transformation based heart energy signature spectrograms. In a pilot trial, we demonstrate its practical feasibility and implementation in the emergency department by utilizing an electronic stethoscope and personal computer.

This method allows S3 detection even with strong background noise. Clinical implementation of our proposed method should lead to improvement in the bedside diagnostic ability of examining physicians, accomplished by increasing the proportion of abnormal heart sounds that are detected.

## 1.0 Introduction

Dyspneic emergency department (ED) patients often present a diagnostic dilemma. Limited tools are available to ED clinicians to aid in accurate diagnosis. As a result up to 15-20% of dyspneic ED patients are misdiagnosed, resulting in a delay to definitive therapy and increased morbidity and mortality [1]. Relying solely on history and physical examination is traditionally problematic. It was recently demonstrated that S3 heart sound has excellent specificity and moderate sensitivity for heart failure diagnosis [2], very good sensitivity and specificity for BNP level elevation [3], and for ejection fraction dysfunction below 30% [4]. Background noise makes S3 detection very difficult in the ED, lowering sensitivity considerably.

### 1.1 Heart Failure Diagnosis

Heart failure (HF) is a disease of epidemic proportions. More than 4.5 million Americans have HF, with about 550,000 new cases diagnosed each year [4]. HF patients are a cohort with significant morbidity and mortality and one-third of known HF patients are admitted to the hospital each year.

Of primary importance in the management of HF is a well-defined method of diagnosing the condition. A definitive diagnosis of HF is often based on right heart catheterization results or indirect measurement of ejection fraction via radionuclide scanning or echocardiography. Lack of immediate availability and cost make these studies prohibitive as ED screening tests. As a result, an ED diagnosis of HF is often based on history and physical exam findings along with ancillary tests such as chest radiography and electrocardiography. Unfortunately, readily available tests such as chest radiography and electrocardiography are often inaccurate as well. Twenty percent of cardiomegaly seen on echocardiogram is missed on chest x-ray [8]. The cardiothoracic ratio is unreliable in predicting left ventricular dysfunction [9], and pulmonary congestion can be minimal or absent in patients with significantly elevated pulmonary artery wedge pressures [10]. While not diagnostic for heart failure, the electrocardiogram can be mildly helpful. Anterior q waves and left bundle branch block both have high specificities, but lack the sensitivity to act as a major screening tool [11,12]. It is clear that distinguishing between cardiac and non-cardiac causes of dyspnea relying solely on these tests is difficult. As a result the clinician must rely heavily on history and physical examination to determine the likelihood of HF.

**1.2 Significance of S3 and S4 sounds detection for Heart Failure Patients**

In modern clinical medicine Potain (1900) [13] and Obraztzov (1910) [14] connected an appearance of the additional (third) heart sound with significant heart abnormalities.

The third heart sound (S3) occurs 0.12 to 0.16 seconds after the second heart sound. Of the many proposed theories, the most likely explanation is that excessive rapid filling of a stiff ventricle is suddenly halted, causing vibrations that are audible as the third heart sound [15]. The fourth heart sound (S4) occurs just before the first heart sound in the cardiac cycle. It is produced in late diastole as a result of atrial contraction causing vibrations of the LV muscle, mitral valve apparatus, and LV blood mass [16]. . Heart failure may be due to deficient pump function during contraction (systolic) or during relaxation (diastolic). S3 may be encountered in either circumstance.

While having a high specificity for elevated filling pressures, jugular venous distention and an S3 heart sound have been reported to have sensitivities of only 30% and 24% respectively [17,18]. More sophisticated examination techniques, such as the Valsalva maneuver, have been shown to improve the sensitivity of physical examination for detection of left ventricular dysfunction in a highly selected group of patients. However, this requires stable, cooperative patients that are able to hold their breath [19]. Other signs and symptoms of fluid overload such as lower extremity edema and dyspnea again raise the suspicion of acute HF, but their lack of sensitivity makes them poor screening tools.

While detection of an S3 can be “normal” in adolescents and young adults, its detection after the age of 40 is considered abnormal [20,21,22]. Traditionally not very sensitive for left ventricular dysfunction, when detected, an S3 can be very predictive of elevated left ventricular pressure. In a study of outpatients referred for cardiac catheterization, the detection of an S3 was the most specific finding of left ventricular end diastolic pressure (LVEDP) (95%) [23]. Another study [5] has also found that the sensitivity and specificity for the S3 in detecting abnormal systolic function (ejection fraction < 50%) were 51% and 90%, respectively. For an ejection fraction of less than 30%, the S3 had a sensitivity and specificity of 78% and 88%. Among patients with acute coronary syndrome, the sensitivity of the third heart sound to detect an ejection fraction <45% was 67.9% while the specificity was 74.4%.[3], Even more importantly, it has been suggested that patients with a detectable S3 have an increased risk of hospitalization and death compared to those patients without a detectable S3 [24,25,26,27]. In the aforementioned studies that suggest a low incidence of S3 detection in heart failure, perhaps the physicians were not able to detect a sound that was indeed present.

Previous phonocardiographic studies have found a prevalence of a fourth heart sound (S4) from as low as 11% [28] to as high as 75% [29] as well as many values in between [30-35]. It is not clear whether the presence of an audible S4 is predictive of cardiac disease. Spodick and Quarry found the presence of an S4 to be no more common in patients with heart disease than those without [31].

Recent studies indicate that physicians are becoming less proficient at performing the physical examination, and physicians in residency programs have been shown to have poor cardiac auscultatory skills [36- 39]. Furthermore, interobserver agreement of S3 detection is poor, with board-certified cardiologists having no better agreement than house staff [40-42]. The low frequency range of the S3 and S4 make their detection difficult [43-45]. The low frequency range overlaps that of other normal heart sounds and murmurs. Compounding the difficulty of S3/S4 detection is that the ED environment is often loud, patients have many confounding illnesses such as COPD and obesity that make detection difficult, and the patient cannot tolerate being placed in the ideal examining position (recumbent) because of their dyspnea.

While S3/S4 detection may be useful as a diagnostic and prognostic tool in ED patients with dyspnea, the traditional method of auscultation has significant shortcomings. With the development of phonocardiography our ability to detect extra heart sounds should improve, eventually leading to improved diagnostic and prognostic abilities. Recent studies used a coupled ECG/phonocardiographic method [2, 46, 47, 48] and demonstrated that sensitivity of HF detection using S3 sounds can be raised to 50%. However their detection threshold does not take into account possibility of intermittent S3 sounds, perhaps eliminating them prematurely, which lowers sensitivity. This method is sensitive to noise, so its detection ability is also sharply reduced if significant noise is present.

Rapid BNP tests present a promising new tool for HF diagnosis. Further, recent research [3] demonstrated a very high correlation between the S3 heart sound and elevated BNP levels, with sensitivity of 65% and specificity of 92%.

Other recent publications [2,24] demonstrated very convincingly the high specificity of an S3 heart sound for LVD and HF, and that digital auscultation can improve sensitivity to 50%. While new rapid BNP tests are very promising and take only 15 min to process, S3 detection at the point of care using the heart sounds can be almost instantaneous.

It was also demonstrated the S3 will disappear under the influence of ACE inhibitors and diuretics, similar to studies revealing corresponding drops in BNP levels. [6, 48] It is clear that successful HF management can lead to a reduction of BNP and disappearance of the S3, which are both positive signs. However, milder forms of HF may not have an S3, leading to a decrease in sensitivity. [3,6]

Glower et al. [49] studied correlations between S3 frequency and intensity with diastolic filling pressure, wall mass and filling rate in dogs . Baracca et al. [50a,50b] developed elastic and viscoelastic vibration models composed of mass and elastic element to non-invasively study S3 sound properties (frequency, intensity) with filling pressures, elasticity, stiffness and heart mass. They concluded that mechanical stiffness can be directly calculated from peak frequency and left ventricular mass at the moment of S3. Stiffness was significantly increased in the HF group. Other have found [49] that wall vibration frequencies associated with an S3 go up (so stiffness goes up) with increases in diastolic pressure or filling rate. S3 amplitude grew proportionally to the filling rate and frequencies were proportional to the increase in diastolic pressure.

A computer based approach will eliminate interobserver disagreement and raise diagnostic sensitivity. Since current methods offer an "on-off" approach to S3 detection, new methodology is required to detect intermittent S3 sounds. Such approaches must also consider the S3 sound properties previously described and use them in the diagnostic decision-making process. [49,50]

## 2. Methods – Heart Energy Signature Spectrogram

Our approach is based on the discovery of unique self-referencing properties of Heart Energy Signature (HES) spectrograms and their derivatives [51], especially on their ability to resolve heart imperfections and normal sounds simultaneously in time and in frequency (pitch). This offers a qualitative and quantitative means of objective diagnosis.

In general, a normal heart should make less noise than a heart with any type of abnormality. HES spectrogram image processing algorithms are based on several integral equations and are derived from the joint-time frequency transformation of the original heart sound signal. The HES is a new method and format and it is described in detail by the present authors in their patent application [52] and in the recent article in Biomedical Engineering Online [53].

Our proposed method is deterministic, does not require any software "training", and is not dataset dependent. It determines S3 sound presence by visual detection of new energy "blobs" on the spectrogram and its derivatives. It uses quantitative measures to characterize these sound properties and it leaves it up to a physician to use these new measures for subsequent diagnosis or patient status monitoring.

**2.1 Joint Time Frequency Distribution - JTFA**

In order to obtain the HES image, a pseudo-periodic portion of the heart sound containing key elements such as S1 and S2 heart sounds and the sounds in-between them (murmurs, clicks) is processed using joint time-frequency distribution (JTFD). By transforming the heart sound into a time-frequency image a far greater amount of details and information about the heart conditions are revealed than from the phonocardiogram (PCG). Several additional averaged and instantaneous characteristics can be extracted from the main HES image for additional insights. Naturally, comparison of the HES images for various heart conditions is much easier than comparison of heart sounds on PCG or by auscultation.

The key element of the HES [51,52] is the heart sound energy computed with the joint time-frequency distribution (JTFD). Detailed description and validation is given by the present authors in [53]. Pseudo Wigner-Ville method (PWVD) has been selected among JTFDs for its optimal time-frequency concentration [55,56]:

$$PWVD_{xx}(t,f) = \frac{1}{2\pi}\int_{-\infty}^{\infty} x(t+\frac{\tau}{2})\, x^{*}(t-\frac{\tau}{2})\, \mu(\tau)\, e^{-j2\pi f\tau}\, d\tau\,, \tag{1}$$

$$\mu(\tau) = h(\frac{\tau}{2})h^{*}(-\frac{\tau}{2})\,, \qquad h(\tau) = A\exp(-\sigma^{2}\tau^{2})\,, \tag{2}$$

where $A$ and $\sigma$ are real positive constants, $\mu(\tau)$ is the Gaussian sliding window function.

Since for general signals, the PWVD takes on negative values, the absolute positive form $|\,PWVD_{xx}(t,f)\,|$ of the PWVD is used in the format for the HES:

$$E(t,f) = |\,PWVD_{xx}(t,f,A,\sigma)\,|\,, \tag{3}$$

where $A = 1.0$, $\sigma^{2} = 10^{-5}$, $t \in [\tau, \tau+T]$, $f \in [f_1, f_2]$. This guarantees the distribution to be positive in the time-frequency plane and makes the straightforward interpretation of the distribution as the signal energy in the time-frequency domain.

Further details on the computational implementation of the pseudo Wigner Ville distribution are available [52, 55, 56].

The Heart Energy Signature (HES) solves the problems associated with analyzing sounds in the time-frequency domain by presenting a standard format for sound analysis. Qualitative differences between the presented images are obvious.

**2.2 Signal Segmentation and Detection of S3**

Currently, the phonocardiograms are segmented using synchronous phonocardiogram and electrocardiogram (ECG) data recording [2, 46-48]. Both the ECG and the phonocardiogram are plotted under each other along the common time axis. The pulses of the heart's electrical activity recorded by the ECG are used as the trigger marks to distinguish between the individual heart beats. In this study segmentation and S3 detection is accomplished by displaying the heart sound energy as a time-frequency image, the PCG, and the signal power concurrently (Figures 1A and 1B).

The signal power is another additional feature of the HES used in the analysis. The computation of the signal power is done according to the formula:

$$P(t) = \int_0^{f^*} E(t, f)df \ , \tag{4}$$

where $E(t,f)$ is the heart sound energy in the time-frequency domain, $[0,f^*]$ is the range on the frequencies used to compute signal power (typically, $f^*$ is one-forth of the signal sampling frequency). The signal power represents the total amount of the energy of the heart sound at any instant of time.

The second graph on the Figure 1B shows the signal power for 3 consecutive heart beats. As can be seen from the plot, the signal power for the S3 sound is lower in intensity (amplitude of the signal power curve) than for S1. The plot also helps in timing the S3 with respect to S1 and S2 heart sounds.

According to [49, 50] the frequency characteristics can also be an important means of detecting and characterizing S3 sound .

We can derive the instantaneous mean and peak frequency of the heart sound signal, corresponding to *E(t,f):*

Instant peak frequency (IPF)= frequency $f^*$ for given $t^*$, for which

$$E(t^*,f^*) = \text{Max}(E(t^*,f)) \tag{5}$$

Instant mean frequency, or IMF, defined as

$$f^* = \frac{\int_{f0}^{f1} E(t^*, f) * f df}{\int_{f0}^{f1} E(t^*, f) df} \tag{6}$$

Instant peak frequency (IPF) is used in this study and is shown on the lower plot on Fig. 1B.

**2.3 Data Collection for the Study.**

We enrolled a convenience sample of patients over the age of 50 that presented to an urban, Level 1 ED (annual census 75,000) with complaints consistent with HF (dyspnea, fatigue or edema). Prior to treatment, with diuretics or vasodilators, subjects were approached for inclusion in the study. Final diagnoses were based on the ED attending physician discharge summary. Those who provide written informed consent had their heart sounds and heart energy signature captured, 15 seconds of heart beats were collected at the apex in the supine position. We utilized the Welch Allyn Master Elite Meditron electronic stethoscope (Welch Allyn Inc., NY) with the piezoelectric contact sensor. It demonstrates good noise-resistance to the acoustic background and low frequency attenuation characteristics. Hearts sounds were recorded using an audio cable connection between the stethoscope and the iRiver 890 (iRiver America Inc, San Jose, CA) compact MP3 recording device (player). Each subject was de-identified and assigned a unique study identification number. De-identified electronic data were subsequently transferred from the recording device to a laptop where it was stored and processed using Bsignal Heart Energy Signature Visualization System V3.5 software (Biosignetics Corp, Exeter, NH).

**3.0 Results and Discussion**

In this paper we provide a comparison of the clinical data obtained in normal office conditions (using data from one of the authors –ADM) and presented in the auscultation training course [57] with the data obtained in ED conditions during our pilot study. This comparison allows to first illustrate expected results (in best conditions) and higher fidelity and then to compare it against the very challenging and noisy ED environment.

**3.1 Analyzing Auscultation Results**

On Figures 1 (A,B) we present a phonocardiogram with a normal physiological S3 (18 year old patient) and heart energy signature time-varying components (image, integral power plot and instantaneous frequency plots). This normal sound was clinically diagnosed by one of the authors (ADM) and included in the database [57]. S1, S2 and S3 components are marked. We can clearly identify S3 energy blob on the image spectrogram, its frequency boundaries and timing. S3 power and timing is also clearly evidenced from the power plot. Note characteristic triple peak pattern. Time dependent frequency plot also clearly demonstrates timing of the events and allows identifying frequency variation for each sound component. We can see that for a normal heart S3 sound has comparable frequency with S2 sound changing between 60 and 100 Hz. Here, elevated S3 frequency is most likely due to smaller ventricular mass and higher output, typical for a young patient.

On Figure 2(A,B) we present similarly structured output plots, but this time for a 70 year old patient with heart failure and a summation gallop (combined S3 and S4) determined clinically by auscultation. In this patient heart sounds were difficult to hear, and correspondingly signal plot (Figure 2A) is considerably more complex. S1 heart sound was soft (low amplitude). In this case S1 energy blobs are weak, and energy signature may not demonstrate clear "triple" pattern (Figure 2B). However, power plot demonstrates triple pattern, with weak S1 and S3 and accentuated S2. S2 is also clearly seen on the energy signature image. S2 sounds reach much higher frequency spectra in comparison with S3, with S3s being closer to 40Hz. Frequency plot also shows a clear pattern of events, showing S1 sounds even when signal power of these sounds is very weak.

On Figure 3(A,B) we present data for an 80 year old male who had a history of myocardial infarction and developed acute heart failure. Abnormal apical sounds of summation gallop were heard on auscultation. In sharp contrast with Figure 1A, heart sound signal that is presented on Figure 3A is not easy to analyze

or segment. A repetitive pattern of 4 components can be identified, but it is not easy to conclude which are S1,S2, S3. Subsequent analysis of combined plots of heart energy signature, power and frequency allowed clear identification of a 4 component pattern. Frequency plots aid in identifying individual components and helps to separate them by their individual frequencies. In this instance S3 and S4 have lower frequencies (below 50Hz) and other sound components have much higher frequencies.

In Figure 4(A,B,C) we compare time averaged frequency characteristics (energy density spectrums) of the above described gallop sounds that were extracted from the heart energy signature image. Figure 4 – comparison of frequency distributions between physiological S3 in a young patient, and in two patients with heart failure. Table 1 summarizes the data presented on these plots. A physiological S3 sound has a mean frequency of 95 Hz with the bandwidth of 67Hz and HF patients have almost twice lower mean frequency (45-52Hz) and narrower bandwidth. While more studies are required to further confirm this finding, it represents an important result that can be utilized to differentiate normal S3 from an abnormal S3. Other studies [49, 50a, 50b] land further support to the importance of S3 frequency and its ability to characterize ventricular dysfunction.

**3.2. Emergency Room Results**

In the second portion of the study we analyzed data obtained from the ED that was characterized by a very high degree of background noise. Our objective was to demonstrate that for the HF patients we can obtain similar and systematic diagnostic patterns on the energy signature, power plot and frequency plot for patients with acute HF and that these patterns will be fundamentally insensitive to noise. Our trial data included patients with clinically diagnosed HF and S3 sounds, patients with clinically diagnosed HF and no S3 sounds, patients without HF (other abnormalities) and no S3 sounds. We also had HF patients for whom physicians failed to detect S3 sounds.

Figure 5 (A,B,C) represents an ED HF patient, who has an ejection fraction (EF) of 50%, BNP levels of 753 and S3 detected during the auscultation. The complexity of the phonocardiogram can easily be visualized on Figure 5A, with arrows showing “suspicious” triple patterns. Detailed view of a smaller time segment is presented on Figure 5B, where we mark S1, S2 and S3 components on a signal plot. This plot is noisy and component identification is difficult. The heart energy signature plot presented on Figure 5C and matching power plot allows to clearly detect repetitive triple patterns of sound (see the red box, S3 sounds are marked on power plot as white arrows). While it is generally possible to detect “pseudo”

sounds due to various ED noises, repetitive patterns confirm their physiological nature. Strong background noise (seen on Figures 5A,B) is virtually eliminated on the HES spectrogram of Figure 5C.

Figure 6 provides detailed time average frequency characteristics of the S3 sound extracted from Figure 5C. Peak frequency of 40Hz is detected, with mean frequency being equal to 44Hz and frequency band being 40Hz. Lower and higher frequency boundaries are demonstrated. Results are also consistent with the data presented in Figure 4, where we demonstrated that heart failure patients have lower frequency below 50Hz.

On Figure 7 (A,B) we present data for another ED HF patient, with a clinically auscultated S3, EF 45% and a high BNP level of 3060. Results of Figure 7A show considerable noise present in the signal that makes it virtually impossible to manually separate sound components. However, energy signature, power and frequency plots presented on Figure 7B shows repetitive 4 peak patterns, indicating presence of both S3 and S4 sounds.

On Figure 8(A,B,C) we present results for an ED HF patient who did not have an S3 detected by auscultation. Detailed analysis of the energy signature and of the power plot allowed to identify repetitive "triple" patterns (that were missed during clinical auscultation in ED), thus hinting at the presence of the S3 sound. This result demonstrates, that presented method allows to extend its applicability beyond human auditory perception and to generate more accurate diagnosis. Further studies will be needed to confirm this.

On Figure 9(A,B) we present results for an ED patient with pulmonary edema (not secondary to heart failure) and no auscultable S3. On Figures 9 (B,C) we clearly demonstrate repetitive "double" pattern that corresponds with S1 and S2 and no S3 present, thus confirming clinical ED finding. S1 and S2 pairs are marked on the figures. While some noise is still present on the phonocardiogram (Figure 9A), it is completely eliminated on the spectrogram and its derivatives, with both power and frequency plots being very clear of artifacts.

On Figure 10(A,B) we present very noisy ED results for a patient who has the same clinical diagnosis as on Figures (9A,B) -- pulmonary edema and no S3. Again, and even in a strong noise background, we can differentiate repetitive S1 and S2 ("double") pattern in a very complex signal presented in Figure 10A.

### 3.3 Discussion

We report on a new technology developed to aid the clinician with bedside detection of abnormal heart sounds. Heart energy signature software converts complex multi-component non-gaussian heart sounds into simple and self-referencing images [52,53]. These provide unique and valuable information to the examining physician at the bedside about pathologic heart sounds (S3/S4) and murmurs. This software is based on BSignal application that reads sound, vibration or any other dynamic time-varying data files (such as EEC, brainwaves, biosignals, acoustic signals, etc.) and processes them to estimate characteristic energy signatures jointly in time and frequency space. This technology allows ultra-fast and memory effective computation, provides convenient post-processing options and a graphical-user interface.

Third heart sound is elicited by the doctor with the patient lying on his left side and the bell of the stethoscope lightly placed over the cardiac impulse. Dynamic auscultation can be used to bring out the sound which is softer in the sitting position than in the left recumbent position. S3 can be heard just beneath the breast bone in a patient with right heart failure. In this event, the sound is brought out on deep breathing held in contrast with the S3 heard from the left ventricle with the patient in full expiration. This is due to the fact that filling of the right heart is increased during inspiration and auscultation of the left ventricle is potentiated by expiration. In the current context, physicians seldom employ these specific techniques previously described [57 ]. It is precisely for this reason that a mechanical technique may assist physicians in their quest for heart failure.

While the S3 gallop may be difficult to detect in the noisy and chaotic ED, its presence has a high specificity and positive likelihood ratio for the presence of heart failure, even among those with underlying pulmonary disease. Newer technologies for the electronic detection of heart sounds should improve significantly the clinicians' ability to detect abnormal extra heart sounds in the ED, and lead to improved diagnostic and prognostic abilities. These tools may potentially be used to grade the severity of heart failure, track responses to therapeutic interventions or even follow the course of disease.

### 4.0 Recommendations for Future Studies

While electronic capture and analysis of heart sounds shows great promise, several hurdles need to be addressed before widespread clinical adoption. First, improvements in analysis to better account for background clinical noise needs to be accomplished. Second, investigations into the optimal equipment needed for bedside use need to be performed. Third, the interface with the physician needs to be made

"user-friendly". Fourth, more data is needed to quantify the relative strength of abnormal heart sounds and how these might relate to clinical outcome.

## 5. Conclusions

We present a new method utilizing a computational approach in conjunction with a point-of-care recording electronic stethoscope (Welch Allyn Meditron), and an iRiver MP3 recording device. We have demonstrated its feasibility and applications for detecting S3 heart sounds in HF patients, including those presenting acutely to the ED.

We used clinically recorded heart sounds of HF patients (collected by one of the authors) to demonstrate this method's feasibility to detect S3 in non-ED condition. We compared these results with results obtained in ED conditions and show that ED files are much nosier. Heart failure S3 sounds are lower in frequency then physiological S3 sounds in young patients (high output states).

For data collected in ED we were able to

a) confirm physician's diagnosis when S3 and HF is present
b) confirm physician's diagnosis for lack of S3 when HF is present
c) detect S3 when physician fails to correctly identify S3 in HF patient
c) confirm physician's diagnosis for lack of S3 in non-HF patient

These findings demonstrate this method's feasibility of correctly detecting S3 sounds in noisy ED backgrounds.

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