

CMR for Assessment of Valvular Disease

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Introduction

Surgical treatment of valvular heart disease (VHD) has the potential to revolutionize the lives of affected patients. Unfortunately, surgery carries the peri-operative risks of stroke, myocardial infarction and occasionally death. Longer term risks include anticoagulation for mechanical valves and the need for re-operation particularly in patients receiving bio-prosthetic valves. In patients presenting or being followed with VHD, decisions need to be made regarding appropriate medical therapy and when this should give way to surgical management. In addition to clinical factors, these decisions are dependent on the type and severity of the lesion, the presence of cardiac decompensation, and also in part on the type of operation required. Cardiac magnetic resonance (CMR) is able to provide accurate quantitative and qualitative data to inform this decision-making process. We review typical applications of CMR in the assessment of VHD, focusing on common indications, case reviews and current limitations, and concluding with exciting new applications in the area of valve mapping.

Background

The majority of stenotic and regurgitant VHD affects the mitral and aortic valves and is either congenital in origin, or acquired as a result of degenerative processes, rheumatic fever, infective endocarditis or ischaemic heart disease. This article overviews practical methodologies which can be used to investigate aortic regurgitation (AR), aortic stenosis (AS) and mitral regurgitation (MR), accompanied by general comments on velocity and flow imaging.

The decision to proceed with medical or surgical

treatment is currently typically based on clinical symptoms and an echocardiographic study. Echocardiography is readily available, portable, inexpensive and achieves high temporal and spatial resolution and is therefore well established in the evaluation of VHD. It is particularly well suited to the visualization of small valvular vegetations in endocarditis. It has the disadvantages of limited acoustic windows, poor image quality in obese patients or those with pulmonary disease, difficulties with consistently aligning a Doppler beam along the direction of blood flow and variability due in part to operator dependence. Doppler techniques are able to measure velocity with precision, but this is not always reflected in flow volumes.

The advantages of CMR for the evaluation of VHD include –

- flexibility to acquire flow or anatomical studies in any arbitrary plane,
- high-quality images (without requiring acoustic windows) in virtually all patients,
- accurate and reproducible measurements of velocity and flow, and
- the ability to consistently perform a full valvular study including ventricular volumes, hemodynamic evaluation and anatomical morphology.

The CMR assessment of stenotic, regurgitant or mixed VHD can be divided into three main components:

- (1) An assessment of the consequences of the valve lesion on left and right ventricular function and mass (see article on ventricular function) and effect on aortic and atrial size,
- (2) haemodynamic evaluation of lesion severity by measurement of stenotic velocities or

CMR is able to provide accurate quantitative and qualitative data to support the decision-making process of therapy in valvular disease.

CMR allows a comprehensive evaluation of valvular disease by imaging morphology, hemodynamics and ventricular volumes.

regurgitant volumes, and
(3) anatomical imaging including planimetry of the valve orifice, and direct visualization of the valve and leaflet morphology.

Many previous difficulties with valvular MR such as dealing with arrhythmias, difficulty with direct visualization of leaflet morphology and time required to perform quantitative post-processing have improved significantly over the last few years. CMR is now complementary to echocardiography and can offer precise additional important information on regurgitant volume, valve geometry and lesion severity.

Indications for CMR in valvular disease

In 2006 the American College of Cardiology Foundation [1] (in conjunction with other professional bodies including the Society for Cardiovascular Magnetic Resonance) gave CMR an appropriateness rating for "Characterization of native and prosthetic cardiac valves – including planimetry of stenotic disease and quantification of regurgitant disease" and "Patients with technically limited images from echocardiogram or TEE" of 'A' with a score of 8/9. An appropriate imaging study was defined as one "in which the expected incremental information, combined with clinical judgment, exceeded the expected negative consequences (defined as procedural risks, and the impact of false negatives or false positives) by a sufficiently wide margin that the procedure was generally considered acceptable care and a reasonable approach for the indication". CMR therefore plays an important role where echocardiographic windows are poor, there are contraindications to TEE, where a high degree of accuracy

is desirable or where the study forms part of a broader investigation already being performed by MR (for example in congenital heart disease). Standard contraindications to MR apply including pacemakers, ventricular assist devices and implanted defibrillators but prosthetic valves are safe in field strengths up to 1.5 Tesla. Although magnetic forces and heating in the valves are not a cause for concern, the presence of metal may unfortunately produce problematic sequence-dependent local image artifacts.

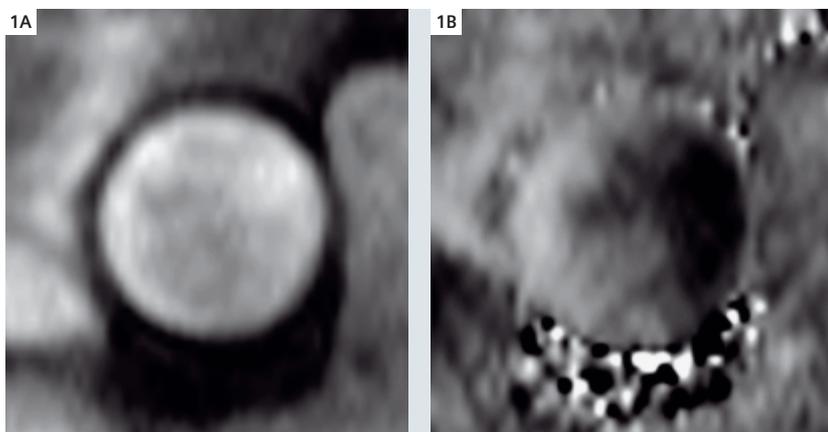
Phase contrast imaging

The mainstay of haemodynamic evaluation is phase contrast (PC) imaging. In a standard MR image, each small image element (known as a pixel) contains a single grey-scale value. In a PC study there are two images as each pixel contains two values, one for the signal intensity (magnitude) and the second for the velocity of blood flowing through the image plane (phase). In the velocity image, mid-grey represents stationary tissue, white the maximum velocity in the through-plane direction, and black the maximum velocity in the reverse direction (Figure 1).

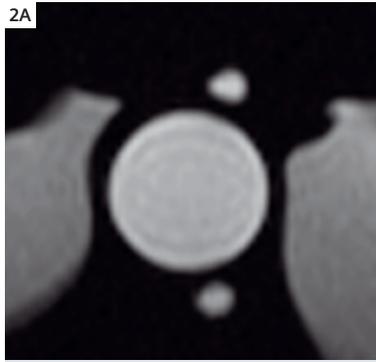
This maximum velocity that can be measured is known as the 'Velocity ENCoding' (VENC) value and this may be set by the user depending on the anticipated peak velocity in the vessel of interest. Typical VENC's for normal aortic flow are in the region of 150 cm/sec, increasing to 400 cm/sec or more for aortic stenosis. If the VENC is set too low, a problem known as 'aliasing' occurs where the blood velocity exceeds the VENC. In this case aliased pixels which should appear black, appear white (Figure 2), or vice versa, and this prevents quantitative analysis. Aliasing is typically seen on the systolic

CMR is complementary to echocardiography and offers precise information on regurgitant volume, valve geometry and lesion severity.

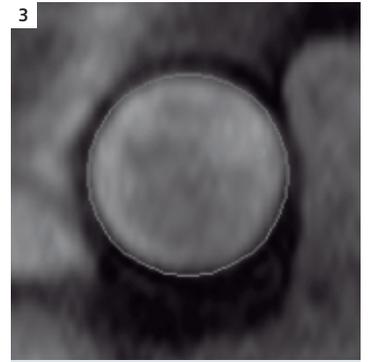
In a phase-contrast study there are two images as each pixel contains two values, one for the signal intensity (magnitude) and the second for the velocity of blood flowing through the image plane (phase).



1 (A) Standard magnitude image of an aorta, and (B) its corresponding velocity or phase image (both at 424 msec after the R-wave). On the phase image, white represents flow through the image plane in one direction and black in the opposite direction. Mid-grey represents stationary tissue. Some diastolic-phase regurgitation is accompanied by forward flow as shown by the presence of black and white regions in the velocity image. "Salt and pepper" or "checker board" noise in the velocity image under the aorta is caused by air in lung tissue where there are insufficient protons to return a reliable signal.



2 (A) Magnitude image of water flowing through a pipe, with (B) its velocity or phase image showing aliasing due to the VENC being set too low. The peripheral slower moving water is correct, but once the velocity reaches and then exceeds the VENC, there is an abrupt transition from black to white where the velocities are no longer correct.



3 Argus contour outlining the region of interest in the aorta. Contouring is performed semi-automatically for each frame through the cardiac cycle cine using both the magnitude and phase images.

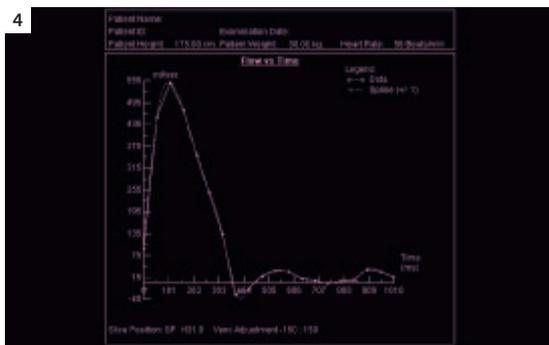
frame because this contains the highest velocities and if this occurs, the sequence should be repeated. If the VENC is set too high, accuracy and signal-to-noise ratio (SNR) is compromised because only a small subset of the available grey scale is utilized. Where the peak velocity is unknown or difficult to estimate, it may be useful to acquire a few velocity scouts to enable the VENC to be chosen with more certainty. The VENC should be set comfortably above (125–150%) the highest velocity expected to be measured.

The main PC planning issues to be considered are to position the imaging slice at approximately right angles to the vessel of interest (small and even

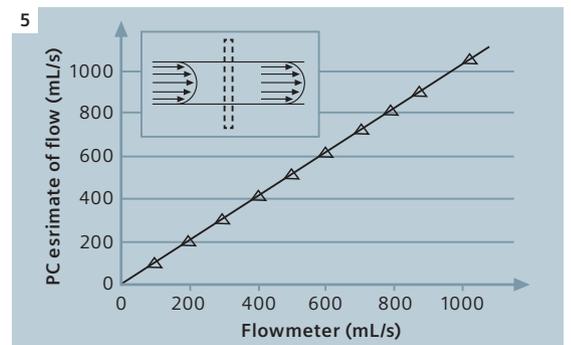
moderate errors in angulation have little or no effect on the flow results but definition of the border of the vessel may be more difficult), choice of the number of frames for the cine (typically 20–30), selection of the VENC, and to select either a breath-hold or free-breathing approach (breath-hold is faster but has lower temporal and spatial resolution).

Once a cine flow series has been acquired, the vessel(s) of interest are outlined semiautomatically on all frames through the cardiac cycle using the Argus Flow analysis software (Figure 3), and the velocity in each pixel within this contour multiplied by its area, and summed to determine the total

The Flow Package contains a Flow Scout which enables fast assessment of up to 5 VENCs.



4 Argus flow-versus-time graph for the aorta. The systolic phase with a peak flow rate of 555 ml/s is followed by very low levels of flow in diastole demonstrating normal valvular function.



5 Validation of phase contrast on a Siemens MAGNETOM Avanto scanner. Water was pumped through a straight pipe (internal diameter 17 mm) and compared to an electromagnetic flowmeter which acted as the gold standard. The maximum error was 2.9% (average error $1.9 \pm 0.7\%$, $r=0.99$).

flow for each frame (Figure 4). Peak and average velocities, net flow and other parameters are then calculated automatically.

The high accuracy of PC imaging during non-pulsatile flow of water through a pipe with a diameter equal to the adult aorta on an Siemens MAGNETOM Avanto system is demonstrated in Figure 5.

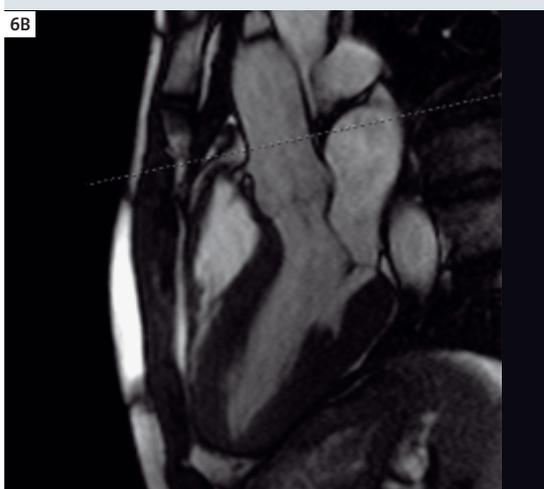
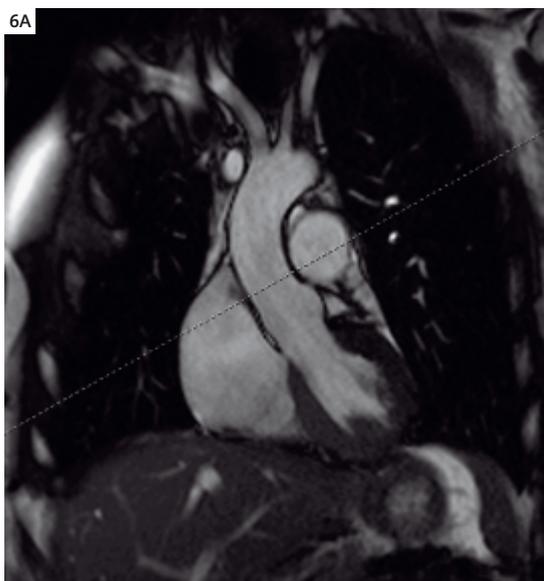
Aortic regurgitation

Case 1: A 25-year-old man presented with dyspnoea and clinical evidence of aortic regurgitation. An initial trans-thoracic echo reported severe aortic regurgitation but was technically limited for left ventricular (LV) and aortic measurements. CMR was requested to better quantify LV size and function, lesion aetiology and severity, and aortic dilatation.

After establishing a good quality ECG signal, the patient was positioned with the phased-array body coil anteriorly and standard cardiac scouts performed followed by breath-hold short and long axis TrueFISP (SSFP) cines for ventricular function. Three parallel oblique coronal slices were planned along the long axis of the aortic root from an axial scout, and the one showing the best view of the aortic root selected to plan the aortic flow study (Figure 6 shows slice planning in a normal volunteer including a three-chamber view). A PC study was acquired using a segmented k-space breath-hold sequence with 24 frames, VENC=150 cm/s, slice thickness 8 mm, pixel size 1.5 x 1.5 mm, and with an acquisition matrix of 192 x 256.

The analysis produced forward and regurgitant volumes of 223 and 90 ml/s respectively from which a regurgitant fraction of 40% was calculated. With an LV end-diastolic volume of 503 ml and end-systolic volume of 280 ml the LV ejection fraction (EF) was reduced at 44%. The aortic root was assessed using standard aortic imaging techniques and showed maximum dilatation at the level of the aortic sinuses of 5.8 cm.

In order to visualize the leaflet morphology, True FISP cine images were obtained in the long and short axes of the aortic valve. The short axis (Figure 7) demonstrated an unusual congenital quadricuspid aortic valve with four unequal cusps and sinuses instead of the normal three. Interestingly each of the two pairs of leaflets were fused, resulting in a functionally bicuspid valve and there was central AR secondary to the leaflet abnormalities. On the basis of this information and the aortic imaging



6 Planning of an aortic flow study in a normal volunteer using (A) an aortic scout and, (B) a three-chamber view.



7 Case 1: Quadricuspid aortic valve (arrowed).

Argus Flow® allows for automatic calculation of peak and average velocities, flow, net flow and other parameters needed for accurate assessment of valvular disease.

Valvular regurgitant fraction can be assessed accurately using PC CMR. Cine images can be used for the evaluation of leaflet morphology.

showing a dilated root and proximal ascending aorta, the patient was referred for aortic valve and root replacement.

Background phase correction

It is common for eddy currents to be induced in the frame of the magnet by the gradients and these can produce a background phase (and hence velocity) signal in stationary tissue. A 'background phase correction' may be applied in Argus Flow by selecting a region of stationary tissue and subtracting this from the results in the vessel of interest.

Although this may provide some correction, unfortunately the background phase is not always constant across the entire FoV and may vary linearly [2], so that the selection of a region of stationary tissue relatively remote from the vessel of interest may introduce additional errors. More recent magnet designs such as the Siemens MAGNETOM Avanto have significantly lower eddy currents compared to older generation magnets and this has significantly reduced this problem. In the future, automated algorithms that calculate the true background phase distribution in all regions of the image are likely to provide a better solution.

Aortic stenosis

Case 2: A 70-year-old man presented with shortness of breath and clinical evidence of aortic stenosis, but had an equivocal echocardiographic study and MRI was requested to image the valve. The peak velocity in the stenotic jet is an important determinant of lesion severity and may be used as part of a calculation of effective valve area. Stenotic jets may be eccentric and the exact position of the maximum velocity may not always be readily apparent. It is possible to acquire multiple PC images transverse to the aortic root and to check each for their maximum velocity, or to acquire a longitudinal view of the aorta using in-plane (as opposed to through-plane) velocity encoding. In this case, three PC slices with a VENC of 400 cm/sec were acquired transverse to the aorta with a peak velocity of 245 cm/sec found in the jet. Valve area was calculated with the continuity equation using PC data obtained from both below the valve in the left ventricular outflow tract and at valve level. Ventricular function was good and in the presence of moderate hypertrophy the criteria for valvular replacement was not met and he was managed medically with regular follow-up.

Accurate assessment of velocity in the jet is essential for reliable diagnosis. Recent data from our laboratory has demonstrated that in the most severe cases of aortic stenosis, where jet velocities can exceed 400 cm/sec with very high levels of turbulence, there can be significant loss of signal due to intra-voxel dephasing and other effects. In order to minimize these effects, it is helpful to keep the TE as short as possible. When signal loss is severe, the PC images may develop evidence of 'salt and pepper' noise (as opposed to aliasing) indicating that the results are likely to be unreliable. When evaluating very high velocity jets, it is important to check the magnitude image in the vessel of interest for dark areas indicative of signal loss and low SNR. The velocity results may be unreliable in these regions, especially if the phase images also contain salt and pepper noise in the same region.

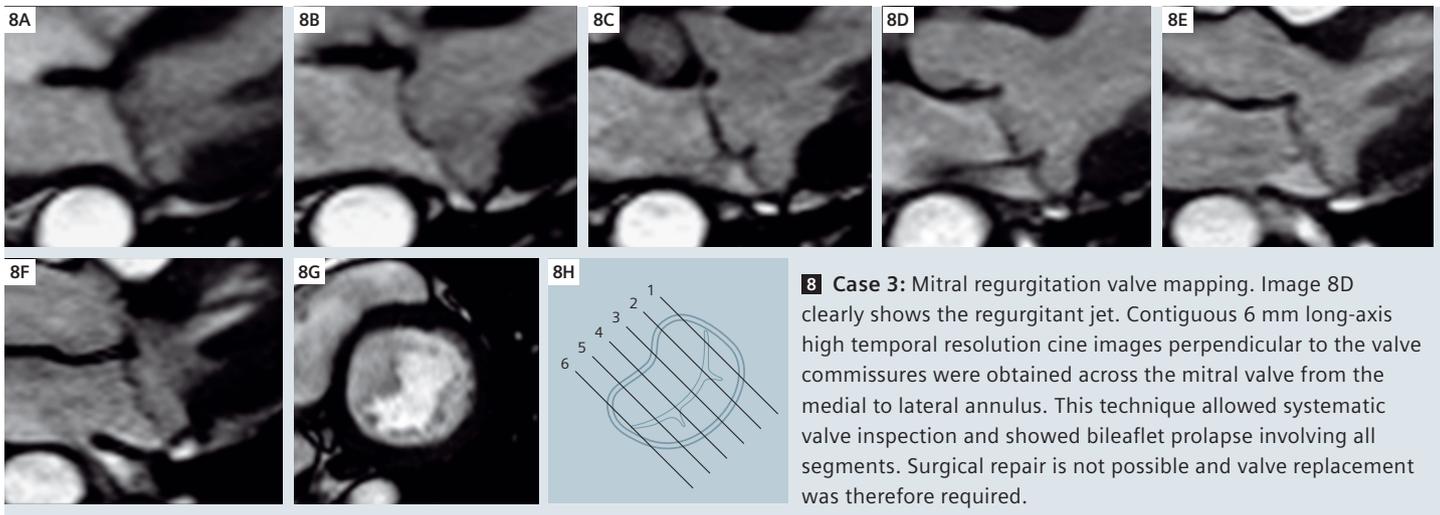
It is common to see flow artifacts in cines which can give a useful subjective impression of any jets or regurgitant flow that may be present. Although correlation with echocardiography has been shown, some caution must be exercised when attempting to accurately quantify or grade the severity of the lesion based on these subjective impressions. These techniques can be useful to quickly determine if there are likely to be solitary or multiple orifices in the valve as can sometimes be seen in mitral regurgitation. True-FISP cines in the plane of the aortic valve may be used to visualize and directly planimeter the area of the systolic opening providing a valve area independent of velocity or flow measurements, pressure gradients or formulae. These have been shown to be correlated with catheterization data and reasonably well correlated to echocardiographic results in aortic stenosis [3].

Mitral regurgitation

Case 3: A 55-year-old woman with a history of rheumatic fever had been followed for mitral regurgitation for 15 years. Her clinical status had deteriorated and there was uncertainty as to whether this was due to her rheumatic valvular disease or other significant co-morbidities including ischaemic heart disease. She was high risk for surgery and was referred for a detailed quantitative evaluation of her valve as part of a delayed enhancement and ventricular function CMR workup. The mitral valve descends by approximately 12 mm

MAGNETOM Avanto has significantly lower eddy currents than older generation magnets, enabling highly reliable flow measurements.

Maximum velocity assessment in stenotic jets can be done using longitudinal in-plane phase-contrast imaging.



during systole, and this movement through a fixed imaging plane makes flow measurement at the mitral annulus challenging. In addition, direct measurement of a regurgitant jet is technically difficult because of jet eccentricity, possible multiple jets, and jet turbulence. It is therefore usual to measure mitral regurgitant volume indirectly by measuring the antegrade flow in the aorta with PC imaging, and comparing this to the ventricular stroke volume calculated from EDV – ESV with the difference representing the mitral regurgitant flow.

The PC flow results from the aorta showed a SV of 65 ml/m², and the ventricular function an EDV of 345 ml/m², ESV of 197 ml/m², SV of 148 ml/m², and ejection fraction of 43%. This equated to a regurgitant fraction of 56% (mitral valve regurgitant volume = LV ventricular SV – aortic SV) at the mitral valve in a dilated and de-compensating ventricle and the patient was referred for surgery. The delayed enhancement scan showed no evidence of previous myocardial infarction. With improvements in hardware and software, it is now possible to acquire high quality images of the mitral valve leaflets in a similar way to those shown for the aortic valve. Generally a thinner slice (5 mm) and increased in-plane and temporal resolution (within the limits of maintaining adequate SNR) are helpful in improving leaflet definition. Leaflets are best appreciated in cine mode, but representative images from across the regurgitant valve are shown in Figure 8. The slices were acquired serially across the valve and are especially useful for mapping leaflet prolapse or defining detailed valve morphology for surgical planning where repair is being contemplated. Left atrial measurements are an important part of

the evaluation and may be made from long axis cine views and volume estimated using standard echocardiographic formulae. If serial short axis slices are acquired through the left atrium, left atrial volume can be measured with more sophisticated software without geometric assumptions. In order to overcome the issues associated with mitral movement, newer research sequences are able to define the motion of the valve annulus and move the imaging slice with the valve through the cardiac cycle to ensure the acquisition remains aligned with the annulus. This technique may make the direct measurement of mitral regurgitant fraction clinically feasible.

Hardware

Most new generation magnets with cardiac gating and post-processing software are capable of performing valvular assessments without additional special equipment. In terms of maintaining flow measurement accuracy, low eddy currents are an important consideration and some older generation magnets with higher eddy currents may not be as well suited to flow studies.

Summary

CMR assessment of valvular disease is an appropriate indication and feasible on current equipment.

References

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- 2 Lankhaar J et al. Correction of phase offset errors in main pulmonary artery flow quantification. *J Mag Res Img* 2005;22:73–79.
- 3 Friedrich MG. Quantification of valvular aortic stenosis by magnetic resonance imaging. *Am Heart J* 2002;144(2):329–34.

Using CMR, high-resolution images of the mitral valve leaflets can be acquired for defining detailed valve morphology.

The Flow Package for image acquisition and Argus Flow* for post-processing are available for all 1.5 and 3T systems.

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