Determination of Optimum Combination of Voxel Size and b-value for Brain Diffusion Tensor Imaging
(Penentuan Gabungan Optimum Saiz Voksel dan Nilai-b untuk Pengimejan Tensor Difusi Otak)

NUR HARTINI MOHD TAIB*, WAN AHMAD KAMIL WAN ABDULLAH, IBRAHIM LUTFI SHUAIB, ENRICO MAGOSSO & SUZANA MAT ISA

ABSTRACT

Optimum combination of voxel size resolution and b-value for whole brain imaging has been determined. Data images were acquired using a 1.5T magnetic resonance imaging (MRI) system (GE Signa HDxt). Diffusion tensor imaging (DTI) scan was performed on phantom and a volunteer. Six protocols which consist of various combination of voxel size and b-value were evaluated. Measurement of signal-to-noise ratio (SNR) and DTI parameter indices were carried out for both phantom and in-vivo studies. Due consideration was given to a combination of parameters yielding sufficient SNR with DTI values comparable to those obtained from previous reported studies. For the phantom study, SNR ≥ 20 was found in all of the protocols except for a combination of voxel size of 2.0 × 2.0 × 2.0 mm³ with b-value of 1200 s/mm² (V2.0 B1200) and that of voxel size of 2.0 × 2.0 × 2.0 mm³ with b-value of 1000 s/mm² (V2.0 B1000). For in-vivo study, all protocols presented SNR > 20. It was found that a combination of voxel size of 2.5 × 2.5 × 2.5 mm³ with b-value of 1000 s/mm² (V2.5 B1000) and that of voxel size of 2.5 × 2.5 × 2.5 mm³ with b-value of 700 s/mm² (V2.5 B700) displayed the most comparable ADC and FA values with references. In terms of anatomic coverage, V2.5 B700 was found better than V2.5 B1000 as it assures coverage of the whole brain. In conclusion, a combination of voxel size of 2.5 × 2.5 × 2.5 mm³ with b-value of 700 s/mm² was considered as optimum parameters for brain DTI.

Keywords: Brain imaging; b-value; diffusion tensor imaging; optimization; voxel size

INTRODUCTION

Recently, diffusion tensor imaging (DTI) has become established as a tool for brain imaging. DTI measures signal attenuation from diffusion of water molecules present in brain tissues and has many advantages over other conventional magnetic resonance imaging (MRI) techniques as it gives tissue information at macro and micro structural level. The example of parameter indices derived from DTI are apparent diffusion coefficient (ADC) or mean diffusivity (MD) which characterises molecular diffusivity and fractional anisotropy (FA) which quantitatively describes molecular diffusivity variation in different directions (Jones et al. 1999; Le Bihan et al. 2001). Moreover, by using DTI technique, visualisation of white matter tracts architecture is available, which opened doors to inspection of microstructural integrity and connectivity of normal and diseased white matter neuronal fibres (Chanraud et al. 2010; Madden et al. 2009).

However, the anisotropy indices are dependent on signal-to-noise ratio (SNR) (Mori 2007; Mukherjee et al. 2008a). Several imaging parameters influencing SNR of magnetic resonance images are described by the equation:
The phantom was placed in an eight-channel MRI scanner room all the time and at scanning time, the temperature of phantom was recorded, that was 20°C.

Human volunteer A healthy female volunteer aged 30.5 years participated in the study. The subject never had any brain injury, neurological or psychiatric illness. The subject signed an informed consent form in compliance with the regulations of the institutional ethics committee.

MR IMAGING

Phantom study The phantom was placed in an eight-channel neurovascular array (NVA) coil for scanning. DTI data were acquired using a 1.5T MRI system (GE Signa HDxT) with maximum gradient amplitude of 33 mT/m. The voxel size resolution was varied at 2.0 × 2.0 × 2.0 mm³ and 2.5 × 2.5 × 2.5 mm³ and the b-value was varied at 700, 1000 and 1200 s/mm². Array Spatial Sensitivity Encoding Technique (ASSET) parallel imaging technique was utilized in the study (King 2004). All other scan parameters were fixed to a specific value, as described in Tables 1 and 2. The whole scan consist of six protocols and the entire scan was performed three times for reproducibility study. While repeating the scanning, the second and the third scan were performed after 1 h interval to allow the temperature of phantom and scanner cooled down to their initial state. This is to minimize the effect of radio frequency heating on phantom which will affect the ADC and FA values acquired.

In-vivo study During in-vivo study, subject’s head was placed in the same NVA coil. The scanning was carried out for all protocols listed in Table 2. No scan repetition was performed as it is unnecessary and unpractical, as discussed further in the Limitations and recommendation for future work section.

DATA ANALYSIS

All data images were transferred to an independent workstation for post processing. SNR and diffusion parameter indices were measured using preinstalled software, Advance Workstation viewer version 4.3 and Functool version 4.5.1 with Fibertrak option (GE Medical Systems), respectively.

Measurement of signal-to-noise ratio For the phantom data, SNR was measured on the centre slice of b₀ images of phantom. One circular region of interest (ROI) with diameter of 15 cm was placed at the centre of the image, covering at least 75% of the phantom area. As for in-vivo study, SNR was also measured on b₀ images of the data. ROI was located on the axial slice at the horizontal level of the striatum containing genu and splenium of the corpus callosum. A square ROI of 16.0 ± 2.0 mm² was drawn manually in right and left white matter (WM) and grey matter (GM) areas, as described previously (Mohd Taib et al. 2012). SNR measured at all ROIs in respective white and grey matter was averaged out. ROIs were also placed in region of cerebrospinal fluid (CSF) at another different slice.

\[
SNR = \left( \frac{FOV_x}{N_x} \cdot \frac{FOV_y}{N_y} \cdot \Delta z \right) \sqrt{\frac{N_s \cdot N_r \cdot NEX}{RBW}},
\]

where \( FOV_x \) and \( FOV_y \) are field-of-view in phase- and frequency-directions, respectively, \( N_x \) and \( N_y \) are the number of phase- and frequency-encoding matrix, respectively, \( \Delta z \) is slice thickness, \( N_{EX} \) is number of signal averaging, and \( RBW \) is the receiver bandwidth (McRobbie et al. 2006).

In addition to ordinary MRI parameters, the SNR of DTI images are also influenced by its sequence-specific imaging parameters. In DTI images, the signal is measured using signal attenuation which is exponentially correlated with b-value as described in (2). An increase in b-value results in reduction of SNR (Alexander & Barker 2005).

\[
S = S_o e^{-bD},
\]

where \( S \) and \( S_o \) are signal intensity of diffusion- and non-diffusion-weighted magnetization, respectively; \( b \) is b-value; and \( D \) is diffusion coefficient. If parallel imaging technique is used, SNR of accelerated images (SNR₉) reduces due to decrease of data sampling and increase of noise in the image (3) (Reeder et al. 2005).

\[
SNR_{g} = \frac{SNR}{gVR},
\]

where \( SNR_{g} \) is SNR of an equivalent unaccelerated image; \( g \) is g-factor; and \( R (≥ 1) \) is the acceleration factor used during acquisition.

Even though many studies employing DTI are present in literature, until now there has been no specific optimized protocols standardized for a multitude of applications. Optimization requires consideration of four main factors: MRI hardware configuration, available scanning time, anatomic coverage needed and specific anatomic structure to be investigated (Mukherjee et al. 2008a).

Therefore, the aim of the present study was to determine the optimum combination of b-value and voxel size. In order to obtain the optimal parameters, assessment was performed on the SNR and then ADC and FA values of the data images. Due consideration was given to a combination of parameters yielding sufficient SNR as well as DTI values which are comparable to those obtained from previous reported studies (Alexander & Barker 2005; Hunsche et al., 2001; Laganà et al. 2010; Lazar & Alexander 2003; Löbel et al. 2009). The present investigation was performed on phantom and human volunteer.

MATERIALS AND METHODS

SUBJECTS

Phantom A standard spherical TLT head phantom with diameter of 170 mm (GE Healthcare) was used. It was kept in the MRI scanner room all the time and at scanning time, the temperature of phantom was recorded, that was 20°C.
containing the body of lateral ventricles. ROI was located similar to reference for comparison purposes (Ding et al. 2007). For both phantom and in-vivo study, measurement was made in first and second volume of b = 0 images and SNR was calculated using the difference method as proposed by previous studies on influence of parallel imaging technique on SNR of MRI images (Dietrich et al. 2007).

Measurement of DTI parameter indices  
ADC and FA values for all protocols were measured at the same ROI as described previously. The results were compared to previous work which used similar 1.5T MRI system (Alexander & Barker 2005; Hunsche et al. 2001; Löbel et al. 2009). The comparisons are in the form of percentage difference which was calculated as,

\[
\text{Percentage of difference (\%) } = \frac{X_f - X_h}{X_h} \times 100,
\]

(4)

\[
\text{Percentage of difference (\%) } = \frac{X_l - X_i}{X_l} \times 100,
\]

(5)

where \( X_f \) is current finding; \( X_h \) is highest value from reference; and \( X_l \) is lowest value from reference. In the case of current findings are higher than that of highest value from reference, (4) was used, whereas if current findings are less than the lowest value from reference, (5) was used.

**Statistical Analysis**

Independent t-test was used to perform the statistical analysis for comparison of SNR between protocols for phantom and in-vivo study, as well as for comparison of ADC and FA values for phantom study. A 2-tailed, \( p < 0.05 \) was considered significant.

**Results**

**Phantom Study**

Figure 1 presents the SNR value measured on phantom images. All protocols listed in Table 2 showed SNR ≥ 20 except V2.0 B1200 (mean ± standard deviation; 18.83 ± 2.49) and V2.0 B1000 (19.66 ± 1.36). All combinations of voxel size 2.5 × 2.5 × 2.5 mm³ with respective b-value showed SNR relatively two-fold higher than that of voxel size 2.0 × 2.0 × 2.0 mm³ (\( p < 0.05 \)). Meanwhile, although there are trend of SNR increasing with reduction of b-value between similar voxel size, there are no any significant difference was noted. Variance and standard deviation between three measurements was found small.

Figure 2 demonstrates ADC and FA values measured on phantom images. All protocols displayed very slight difference in ADC value with percentage difference ranging from 0.25 to 6.16%. However, the only protocol that displayed significant difference compared to all other protocols is V2.0 B1200. On the other hand, moderate to high variation in FA values exhibited by all protocols (range from 7.08 to 127.59%) achieved significant different. However, a comparison between V2.0 B1200-V2.0 B1000, V2.0 B700-V2.5 B1200, and V2.5 B1000-V2.5 B700 was found insignificant. High standard deviation and variance of ADC and FA values

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**Table 1. The imaging parameters which were kept fixed for all of the protocols**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse sequence</td>
<td>Single shot spin echo, echo planar imaging</td>
</tr>
<tr>
<td>Echo time, TE (ms)</td>
<td>(minimum) subject to b-value</td>
</tr>
<tr>
<td>No. of diffusion directions</td>
<td>30</td>
</tr>
<tr>
<td>No. of unweighted images</td>
<td>3</td>
</tr>
<tr>
<td>ASSET acceleration factor</td>
<td>2</td>
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<tr>
<td>Phase-encoding direction</td>
<td>R/L</td>
</tr>
<tr>
<td>Inter-slice spacing</td>
<td>0</td>
</tr>
<tr>
<td>Receiver bandwidth, RBW (Hz)</td>
<td>1953.12</td>
</tr>
<tr>
<td>Number of signal averaging, NEX</td>
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**Table 2. The imaging parameters that were altered according to the six protocols assessed**

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<tr>
<td>Repetition time, TR (ms)</td>
<td>17 000</td>
<td>13 000</td>
</tr>
<tr>
<td>Field-of-view, FOV (mm²)</td>
<td>256 × 256</td>
<td>240 × 240</td>
</tr>
<tr>
<td>Matrix</td>
<td>128 × 128</td>
<td>96 × 96</td>
</tr>
<tr>
<td>Slice thickness (mm)</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>b-value (s/mm²)</td>
<td>1200</td>
<td>Protocol 1: V2.0 B1200 Protocol 4: V2.5 B1200</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>Protocol 2: V2.0 B1000 Protocol 5: V2.5 B1000</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>Protocol 3: V2.0 B700 Protocol 6: V2.5 B700</td>
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</tr>
<tr>
<td>b-value (s/mm²)</td>
<td>1200</td>
<td>Protocol 1: V2.0 B1200 Protocol 4: V2.5 B1200</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>Protocol 2: V2.0 B1000 Protocol 5: V2.5 B1000</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>Protocol 3: V2.0 B700 Protocol 6: V2.5 B700</td>
</tr>
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were also noted in V2.0 B1200 while moderate of that were seen in V2.0 B1000. It is also noted that V2.0 B700 and V2.5 B700 displayed a comparable ADC values that are $(202.00\pm2.65) \times 10^{-5}$ mm$^2$/s and $(202.50\pm2.50) \times 10^{-5}$ mm$^2$/s, respectively. However, V2.0 B700 showed a higher FA value, that is $(5.08\pm0.10) \times 10^{-2}$ compared to V2.5 B700, that is $(3.95\pm0.02) \times 10^{-2}$.

**IN-VIVO STUDY**

As Figure 3 depicts, all protocols showed SNR of CSF $> 20$. However only V2.5 B1200 displayed significantly higher SNR compared to that of all protocols with voxel size $2.0 \times 2.0 \times 2.0$ mm$^3$. Meanwhile, all combination of voxel size $2.5 \times 2.5 \times 2.5$ mm$^3$ with their respective b-values displayed a fairly but insignificantly higher SNR of WM and GM compared to that of voxel size $2.0 \times 2.0 \times 2.0$ mm$^3$. An insignificantly higher SNR was also noted in GM compared to WM for each of the protocol.

Figure 4 illustrates the ADC and FA values obtained from in-vivo study while Figure 5 presents the percentage difference from the references. In Figure 5, the bars show differences at each ROI for all protocols. Values that matched with previous studies are indicated as 0% differed from references.

From Figure 4, it is noticed that protocols with larger voxel size and smaller b-value produced more comparable results to references. As described in Figure 5(a), protocols that exhibited ADC values with smallest percentage difference compared to previous studies were V2.5 B1000 and V2.5 B700 (3.66-11.13% and 0.49-5.51%, respectively). It can also be seen that V2.0 B1200 and V2.0 B1000 exhibited ADC values which differed considerably from references (6.77-59.18% and 3.40-35.09%, respectively). It was noticed that the difference is obvious mainly in area of genu and splenium. At genu, the greatest difference was 59.18% for V2.0 B1200 and 28.18% for V2.0 B1000, whilst at splenium, the biggest difference was 54.03% and 35.09% for V2.0 B1200 and V2.0 B1000, respectively. Similar outcome was observed for FA values (Figure 5(b)) in which V2.5 B1000 and V2.5 B700 were found least differed to references with percentage of 8.79-19.27% and 4.98-25.55%, respectively, whereas V2.0 B1200 and V2.0 B1000 demonstrated the largest difference (7.96-37.57% and 8.79-47.02%, respectively). In terms of number of ROI, V2.5 B700 was found displaying FA values that matched the references at three ROIs, compared to V2.5 B1000 which shows only two of that.

**DISCUSSION**

**IMAGING PARAMETERS**

As in most of MRI procedure, the goal is to obtain data images with good quality at acceptable scan time. The typical imaging parameters include those mentioned in (1) to (3) and as displayed in Tables 1 and 2. In this study, we tried to vary all related imaging parameters that influence
the SNR. However, since we do not have research level access to the MRI scanner in order to alter all imaging parameters, the RBW, g-factor and acceleration factor were kept constant according to vendor specification. The NEX were fixed to 1 as we aim to keep the scan time as minimum as possible. The TR became fixed by vendor to minimum value subject to b-value used whereas TE were fixed to 17 000 and 13 000 ms for voxel size 2.0 × 2.0 × 2.0 mm³ and 2.5 × 2.5 × 2.5 mm³, respectively, to allow coverage of whole phantom and brain. The number of diffusion direction was also fixed to 30, which is the minimum number required for robust estimation of tensor orientation and mean diffusivity as proposed by Jones (2004). Therefore, in the present study, only two parameters were varied, which are the voxel size (i.e. FOV, matrix and slice thickness) and b-value.

In terms of voxel size, we tried to obtain the smallest voxel size that could be achieved i.e. 2.0 × 2.0 × 2.0 mm³ while trying to compensate for an acceptable SNR and scan time. We chose isotropic voxel based on its advantages over non-isotropic voxels (Jones et al. 2002; Sasaki 2007; Oouchi et al. 2007). We also chose the lowest and highest b-values (700 and 1200 s/mm², respectively) which were testified from previous work that those are the optimal b-value for brain imaging as well as the common b-value used, which is 1000 s/mm² (Bougias & Tripoliti 2009; Mori 2007; Mukherjee et al. 2008a).

ASSESSMENT OF SNR

This study has led to an understanding that the SNR improves with decreasing b-value and with increasing voxel size (Figure 1), which agrees well with the theory (Mukherjee et al. 2008b) and as predicted via (1) and (2). Our findings also matched with previous work on SNR assessment (Laganà et al. 2010; Lazar & Alexander 2003). It is also observed that modifications to the b-value, in our case it ranged from 200 to 500 s/mm², not much affect the SNR. On the other hand, an increase in voxel size of 0.5 × 0.5 × 0.5 mm³ showed SNR enhancement of approximately double. This indicates that the voxel resolution is a more dominating factor affecting the SNR compared to amount of diffusion weighting used.

\*ADC reported as MD in some of the articles referred. \*fWM: frontal white matter; Sp: splenium; cNuc: caudate nucleus; lNuc: lentiform nucleus; Thal: thalamus; oWM: occipital white matter; oGM: occipital grey matter. \*Ref-highest: highest values in reference, Ref-lowest: lowest values in reference.

This study: values obtained in this study

**FIGURE 4.** The ADC\(^a\) and FA values at all ROIs\(^b\) acquired for all of the protocols\(^c\)
It is noted that the SNR must be at least 20 to be considered as sufficient (Bastin et al. 1998; Mukherjee et al. 2008a). Our findings based on phantom study showed all protocols except protocols V2.0 B1200 and V2.0 B1000 provide sufficient SNR. However, measurement of SNR on CSF shows all protocols produce sufficient SNR (Figure 3). This is due to intrinsic characteristics of both phantom and CSF, in which CSF has higher water content, thus appeared more intense than phantom in the b0 images. Therefore, CSF exhibits SNR relatively higher than that of phantom for all protocols.

ADC AND FA VALUES
Influence of SNR on DTI values are also described well by our findings. This study showed that there is variation of ADC and FA value found from phantom measurement. Theoretically, the variation is due to two reasons. Firstly, the amount of diffusion weighting used in the protocol as described in (2) and secondly, bias in ADC and FA estimation caused by an insufficient SNR (Bastin et al. 1998; Mukherjee et al. 2008a).

Our findings showed that protocols with sufficient SNR displayed an insignificant increment of ADC value over smaller b-value. Thus it gives clue that V2.0 B1200 and V2.0 B1000 suffered from insufficient SNR (Figures 1 & 2). In this condition, our finding showed an agreement with a Monte Carlo simulation study which suggested that the ideal SNR is greater than 40 and SNR of less than 20 may results in underestimation of ADC and overestimation of FA (Bastin et al. 1998). A high FA noticed that in V2.0 B1200 does not at all represent the purely isotropic diffusion of the phantom. At the same time, a remarkably high standard deviation and variance of ADC and FA values between the three scans was also noted in V2.0 B1200 and V2.0 B1000 which indicates inconsistency of results (Figure 2).

It is also observed that protocols V2.0 B700 and V2.5 B700 displayed a comparable ADC values but different FA values as depicted in Figure 2. This result also reflects the effect of SNR on both of the protocols. Although the protocols exhibited sufficient SNR, however only V2.5 B700 achieved the ideal SNR as described above, thus it displayed smaller FA values.

Nonetheless, although all protocols with voxel 2.5 × 2.5 × 2.5 mm3 exhibited SNR of 40 and above, the smallest FA value that we could obtain was from protocol V2.5 B700. The FA value recorded is 0.0395 which is 3.95% deviated from the absolute FA value, i.e. zero. Besides
displaying small difference from absolute FA value, our results are comparable with that of obtained by Hunsche et al. (2001).

As can be seen from the in-vivo study (Figure 4), both ADC and FA values are affected by changes in b-value and voxel size. Our results for both phantom and in-vivo studies exhibited a similar trend for all of the protocols. Furthermore, the trend was also consistent with our findings on SNR where the most incomparable DTI values with references were noted in V2.0 B1200 and V2.0 B1000. This corresponds to the lowest and insufficient SNR obtained from phantom study. The effect is especially noticeable in the genu and splenium of the corpus callosum. Possible reason that explained this outcome is that insufficient SNR causes bias in estimating diffusion weighted signals. In case of high anisotropic white matter structure like corpus callosum, they are more greatly affected by insufficient SNR as the water diffusivity along the fibres orientation are less restricted. Thus, the diffusion weighted signals from this area are strongly attenuated, hence overestimated. Overestimation of the signals then leads to underestimation of ADC profile and anisotropy (Jones & Basser 2004; Mukherjee et al. 2008a). In our case, the ADC and FA value of genu and splenium were considerably deviated from previous findings (Figure 5).

Our finding demonstrates that protocols with voxel 2.5 × 2.5 × 2.5 mm³ give the required SNR. In terms of scan time, all of the protocols in this group took similar period to complete each scan which is 7.98 min. As can also be noted in Figures 4 and 5, among the three b-values, protocols V2.5 B1000 and V2.5 B700 displayed the most comparable results with references (Alexander & Barker 2005; Hunsche et al. 2001; Löbel et al. 2009) and only slight differences were noted between both protocols. Thus both protocols meet the requirement for brain imaging. However, when using b-value of 1000 s/mm², the scanner automatically reduces the limit of maximum number of slices allowable for data acquisition due to specific absorption rate (SAR) control. Instead, a protocol that could assure coverage of whole brain for all subjects are required to proceed with the next work on leukoaraiosis (Mohd Taib et al. 2012).

LIMITATIONS AND RECOMMENDATION FOR FUTURE WORK
In this research, no repetition has been done for in-vivo study due to two reasons. Firstly, the aim of in-vivo study was to validate the findings from the phantom study in which the phantom was scanned for three times. Thus, a single in-vivo scanning was reputed sufficient to achieve the objective of verifying the phantom study and that scan repetition is unnecessary. Secondly, the time taken to complete the entire scan is 52.03 min per session in which performing three times scan repetition on human subject is unpractical.

Besides that, single subject was used in this study and the results may not represent inter subject variability. However, our results from in-vivo study present a trend which is concordant with that of obtained from phantom study.

Despite all of the limitations mentioned previously, our findings gave the required information to understand the influence of parameters associated to DTI as well as to choose the best combination of parameters under consideration. Our next task is to study the inter subject variability using the optimum protocol obtained from this study and evaluate the range of DTI values produced by the MRI system.

CONCLUSION
Both phantom and in-vivo studies exhibited the similar trend of SNR values for all protocols. The finding demonstrated that protocols with voxel size of 2.5 × 2.5 × 2.5 mm³ give the desired SNR of at least 20. It was also found that a combination of voxel size of 2.5 × 2.5 × 2.5 mm³ with b-value of 1000 s/mm² (V2.5 B1000) and a combination of voxel size of 2.5 × 2.5 × 2.5 mm³ with b-value of 700 s/mm² (V2.5 B700) displayed the most agreeable results with the references. However, due to SAR limit, a compliant protocol that could assure the coverage of the whole brain for all subjects has to be selected accordingly. In conclusion, a combination of voxel size of 2.5 × 2.5 × 2.5 mm³ with b-value of 700 s/mm² were considered as an optimum parameters for brain DTI.

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