Contrast sensitivity of digital imaging display systems: Contrast threshold dependency on object type and implications for monitor quality assurance and quality control in PACS

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The American Association of Physicists in Medicine Task Group 18 has published standards and quality control (QC) guidelines to ensure consistency and optimal quality for digital image display systems (DIDSs). In many of these recommended QC tests, static test patterns that contain low-contrast objects are often used to assess and validate the quality of a DIDS. These low-contrast objects often have the shape of circular disks or squares with sharp edges, neither of which resemble most of the diagnostic findings in medical images. On the other hand, circular objects with fuzzy boundaries bear a closer resemblance to lung nodules in chest radiography and masses in mammography; thus, they may be more clinically relevant in assessing display system quality. In this article human observers' contrast sensitivities of circular objects with sharp edges and those with fuzzy ones were investigated. The contrast thresholds of human viewers using a consumer-grade color LCD monitor and a medical-grade monochrome LCD monitor were measured for objects of various sizes displayed against uniform backgrounds with various luminance levels. Contrast-detail curves for circular objects with sharp edges and those with fuzzy boundaries were measured and compared. It was found that contrast thresholds for objects with fuzzy boundaries were higher (i.e., the objects were more difficult to detect) than those with sharp edges. Objects with fuzzy boundaries were potentially more sensitive in distinguishing quality differences among image display devices and thus may be a better QC measurement in detecting subtle deterioration in image display devices. © 2009 American Association of Physicists in Medicine.

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I. INTRODUCTION

A contrast-detail (C-D) curve describes the spatial and contrast resolution characteristic of an imaging system. The C-D curve of a digital image display system (DIDS) represents the combined capability of a monitor to display low-contrast objects and a human observer's ability to discern these objects. Points along the curve represent the minimum visible contrast given the object's size. Usually, the vertical axis is the contrast of the object relative to its background while the horizontal axis is the object size. The curve represents the threshold or boundary between objects that can and cannot be visualized; objects with size and contrast above the curve are visible while objects with features that fall below the curve are not. Typical curves have two asymptotes. The vertical asymptote (parallel to the y axis) corresponds to the spatial resolution limit of the system. This asymptote represents the smallest object that can be resolved by the system

regardless of how high the contrast between the background and the object is. The horizontal asymptote (parallel to the x axis) represents the minimum detectable contrast (or contrast resolution) of the system regardless of the object size. For DIDS, contrast thresholds represented by the C-D curve are known to be dependent on several factors, such as the luminance level.

As medical imaging moves toward more reliance on soft-copy image display, the assessment of DIDS' quality and methods for routine QA become more critical for clinical care.¹⁻³² In today's digital world of medicine, variations in the quality of DIDS may have direct impact on diagnosis accuracy and thus patient care quality. For instance, if a low-contrast lesion or pathological condition is present in the digital image but the display system is not adequately or optimally configured, the lesion may be simply invisible to the physician and misdiagnosis may result.

FIG. 1. Intensity line profile of the circular object with sharp edges (left, disklike) and the circular object with fuzzy edges (right, nodular). An object with a line profile similar to that of the x-ray attenuation of a spherical nodule would have fuzzy edges.

Digital Imaging and Communications in Medicine (DICOM) committees and American Association of Physicists in Medicine Task Group 18 (AAPM TG18) have published guidelines and standards for softcopy display systems to ensure the highest quality for clinical diagnosis.³³ Today, most of the routine quality control (QC) tests for DIDS utilize static test patterns containing low-contrast objects that are either line pairs or circular or square objects with sharp edges. Although these targets are acceptable for some of the basic QC measures, they in no way simulate the typical pathological findings in medical images. For instance, lung nodules on chest x-ray radiographs and masses on mammograms closely resemble circular targets with fuzzy boundaries and their x-ray image intensity profiles are very close to those of spheres.

Additionally, our previous studies showed that most of the DICOM-calibrated medical-grade monitors enabled human observers to visualize most circular targets with sharp edges to the minimum threshold allowable in a digital system, i.e., contrast threshold equals to one pixel value.²⁰ Even for some of the consumer-grade color monitors, a majority of the targets with sharp edges were visible. Does that mean that the quality of these consumer-grade monitors is equal to that of the medical-grade ones? Indeed, some anecdotal reports claimed that clinical diagnostic accuracy for cross-sectional images, such as those obtained by CT and MRI, did not differ markedly between the medical-grade monochrome monitors and several off-the-shelf consumer-grade color monitors.²⁰

Finally, it is believed that DICOM standard look-up-table (LUT) calibration will result in linearization of contrast sensitivity for the entire luminance range of the monitors.³³ However, the DICOM LUT was adopted from Barten's model,³⁴ which was based on studies using a target that consisted of a square object containing sinusoidal intensity grading, much like a line pair or bar pattern; therefore, there is some doubt about the relevance of such calibration to medical targets, which most often are circular. One question that remains is how the contrast sensitivity would be linearized for a circular or a nodular target.

In this study, we studied the contrast thresholds of human observers for both circular objects with sharp edges and nodular objects with fuzzy edges in a uniform luminance background. Figure 1 is a schematic of the intensity profiles for these two object types. We studied the detectability of targets with sharp and fuzzy edges and compared results between groups. Our study had two main goals. The first was to find a more sensitive method than the current one to assess the quality of DIDS for monitor QC in PACS. The second aim was to measure the psychophysical effect of contrast threshold dependency upon target shapes (i.e., the sharpness of their edges).

II. MATERIALS AND METHODS

We measured the contrast-detail characteristics of a 17 in. consumer-grade color LCD monitor (MultiSync 1980FXi; 1280×1024 spatial resolution; nominal pixel size of 293 μm ; NEC, Itasca, IL) and a 20 in. monochrome DICOM-calibrated LCD monitor (C3i; 2048×1536 spatial

FIG. 2. Screen capture shots of test image containing (a) a nodular object with fuzzy edge and (b) a circular object with sharp edges on the uniform background. The location of the object varied randomly between test images to minimize any learning effect.

resolution; nominal pixel size of $207 \mu\text{m}$; DOME, Beaverton, OR). Contrast thresholds were measured using an interactive program developed by the authors. Details about this program and the data acquisition process can be found in a previous publication.^{20,35,36} During the current experiments, an observer was presented with a series of test images generated by the program in real time. In each of the test images, there was a single circular object randomly located on a uniform background (as shown in Fig. 2) at the central portion (500×500 pixels) of the monitors. This central portion has the corresponding sizes of $146 \times 146 \text{ mm}^2$ for the color monitor and $103 \times 103 \text{ mm}^2$ for the monochrome monitor. Observers had to interact with the computer by pointing and clicking on the target, and the program automatically recorded the contrast thresholds of the observers for the two types of objects at various object sizes and background luminance levels. No window/level adjustment was allowed; thus the inherent LUT (the input pixel to luminance level

conversion table) was not altered. If the observer pointed and clicked the mouse at the correct location of the object (within preset error margins; approximately twice of the size for small objects and 10% for larger objects), an object with decreased contrast would appear at another random location. The test continued until the observer could no longer correctly identify the object (after three trials). The lowest visible contrast level (measured as the differences in intensity between the object and its uniform background in pixel values) was automatically recorded by the program as the contrast threshold for that particular object size. This procedure was repeated, and contrast-detail curves were obtained by looping over all the predefined object sizes and background levels. Finally, the resultant data were exported to a Microsoft Excel file and evaluated.

Six observers (ages ranged from 24 to 30, medical physics trainees) participated in the studies. Contrast thresholds were measured at four object sizes and five background luminance levels for each monitor in the study. The five luminance levels (at pixel values of 51, 98, 145, 192, and 239 for an 8 bit display system) were selected to simulate the clinical scenario in chest x-ray imaging, where darker background corresponds to the lung field and brighter background corresponds to the mediastinum area. Circular objects with sharp edges (simulating the x-ray attenuation intensity profile of a disklike object) and fuzzy edges (simulating the attenuation intensity profile of a spherical nodule) were presented, with on-screen diameters of 15, 10, 7, and 2.5 mm for the color monitor and 10, 7.5, 5, and 2 mm for the monochrome monitor. During the tests, each viewer was allowed to view the objects at a comfortable normal viewing distance, simulating actual clinic practice. The average viewing distance was approximately at 40 cm. To minimize the effect of target searching, no time restriction was imposed upon the viewer to complete the task. The ambient light level in the room where the study was performed was measured to be approximately 10 lx.

For circular objects with sharp edges (disklike), the contrast threshold was defined as the pixel value at which the object could last be distinguished from its uniform background (Fig. 1). It was calculated simply by subtracting the pixel value of the background from that of the object. The lower the contrast threshold, the less contrast is needed between the object and background for the object to be detected, giving the display system higher contrast sensitivity (and better user performance). The maximum brightness corresponded to an input pixel value of 255 and the minimum brightness corresponded to an input pixel value of zero.

For the circular objects with fuzzy edges (nodular), the contrast threshold was defined as the maximum pixel value at the center of the target that was last discernible. The pixel intensity profile of the nodular object was designed to simulate the x-ray attenuation of a spherical nodule; its intensity profile was scaled by the maximum intensity pixel value, which was also defined as the contrast threshold in the C-D curve measurements (Fig. 1).

Since the main aim of our study was to find a general trend rather than each individual's capability to detect differ-

ences in contrast, all contrast threshold values presented in this paper are averaged over the six observers. Our previous work has shown that intraobserver variations of contrast threshold measured with this tool are consistently within a maximum difference of one pixel value.³⁶

III. RESULTS

III.A. Comparison of the consumer-grade color monitor and the medical-grade monochrome monitor

III.A.1. Contrast threshold measured with circular object with sharp edges

As expected, the monochrome medical-grade monitor had lower contrast thresholds (thus better performance or higher contrast sensitivity) than the consumer-grade color monitor at most background luminance levels and object sizes (Fig. 3). Note in Fig. 3 that for the monochrome medical-grade monitor, most of the contrast thresholds reached one pixel value, which is the lowest contrast possible due to the digital nature of DIDS. Also note that for the consumer-grade color monitor a majority of the contrast thresholds measured with disklike objects also reached one or two pixel values. This may explain some of the previous anecdotal claims in the PACS/informatics community that there were no significant quality differences between commercial-/consumer-grade color monitors and the medical-grade ones, especially when dealing with cross-sectional images.

III.A.2. Contrast threshold measured with nodular object with fuzzy edges

As shown in Fig. 4, when the C-D curves were created using measurements of the detectability of a nodular object with fuzzy edges, the differences between the consumer- and medical-grade monitors became more obvious. Contrast thresholds for the monochrome monitor were lower (thus, they had better contrast sensitivity) across the board (at nearly all background luminance levels and object sizes), indicating that the nodular objects were more difficult to detect than the disklike ones.

III.B. Contrast threshold variances attributed to object-type difference

Within the same monitor group, it was clear that contrast thresholds measured with the disklike object were lower than those measured with the nodular object, validating the past observations of contrast threshold dependency on object type.^{37,38} Figure 5 shows the C-D curves obtained for nodular and disklike objects at five background luminance levels. As shown before in Fig. 3, the contrast thresholds for the disklike object were mostly at or very close to one pixel value except at the smaller object sizes; nodular objects with fuzzy edges were clearly more difficult to detect (i.e., they had higher contrast thresholds). This result can be explained by the fact that the human visual system behaves inherently as a high-pass filter, enabling human beings to detect objects with sharp contours and edges more easily than objects with gradual changes in intensity.

In all the plots shown in Fig. 5, the contrast thresholds for the nodular target have been adjusted by multiplying a factor of 2/3 to account for the “intensity-area” product differences between the two object types (see Sec. IV for details). Note that it still does not come close to mapping the C-D curve of the disklike object onto the curve for the nodular object, indicating that other psychophysical factors, such as the high-pass filter nature of the human eye (i.e., its affinity for edges) contribute to the improved contrast resolution of the circular objects with sharp edges.

III.C. Contrast threshold dependency on background luminance

In Fig. 6 the contrast thresholds for the color and monochrome monitors are plotted as functions of the background luminance level. Contrast thresholds for both nodular and disklike objects are shown.

For the monochrome monitor, the contrast thresholds were nearly independent of the background luminance level and almost equal over the entire luminance range, indicative of the DICOM calibration of the medical-grade monitor and the realization of contrast sensitivity linearization promised by the DICOM standard LUT. These experimental results directly demonstrate that linearization occurs when the standard LUT is applied to nodular objects as well. Since the DICOM LUT was adopted from Barten’s model, which was based on objects with sinusoidal grating (or square objects with line-pair-like intensity modulation), our data demonstrate the direct effects of DICOM calibration on clinically more realistic objects in DIDS.

For the consumer-grade color monitor, however, the effect of background luminance level was more sporadic and variant over the luminance range, indicative of the noncompliance to the DICOM standard LUT and nonlinear contrast sensitivity over the luminance range. This result thus demonstrates the importance of DIDS’ compliance to the DICOM standard LUT for display of medical images and the consequences of noncompliance.

III.D. Statistical analysis

The contrast thresholds of the disklike and nodular targets for all viewers were compared using the Wilcoxon rank-sum test. The rank-sum test was performed independently for both the color monitor group data and the monochrome monitor group data. Within each monitor type, the contrast thresholds of the nodular and the disklike object types were compared. It was found that the overall contrast thresholds for the consumer-grade color monitor were significantly higher than those of the medical-grade monochrome monitor for both nodular and disklike objects ($p < 0.001$). Contrast thresholds for larger objects were significantly lower than those of smaller ones ($p < 0.001$). The contrast thresholds of the nodular objects were significantly higher ($p < 0.0001$) than those of the disklike objects for both monitors.

In comparing the contrast threshold differences measured with the disklike and the nodular objects, thus comparing the ability to differentiate the qualities of the color monitor to

FIG. 3. C-D curves for an off-the-shelf customer-grade color monitor and a medical-grade monochrome monitor for objects with sharp edges viewed against various background luminance levels. These contrast threshold data represent means for six observers.

those of the monochrome monitor, the contrast-detail data were analyzed as follows. For both the color and the monochrome monitor, the contrast-detail curves for both the disk and the nodule were estimated using a low-dimensional spline interpolation. A Bayesian estimation procedure was used to estimate the spline parameters to yield the fitted curves, together with their 95% credible intervals, for both the disklike and nodular objects. Using a grid of 200 evenly

spaced points along the domain of the object size, over which the two curves overlap, we calculated the pointwise differences between the color and the monochrome monitor measured with both the disk and nodule's C-D curves, along with their respective 95% credible intervals. If zero lies in the interval, it is indicative of no significant difference between the two monitors' contrast thresholds measured with the disklike (or nodular) object. On the other hand, if the

FIG. 4. C-D curves for a consumer-grade color monitor and a medical-grade monochrome monitor for objects with fuzzy edges viewed against various background luminance levels. These contrast threshold data represent means for six observers.

95% credible intervals of the pointwise difference curve are above zero, it indicates that the contrast threshold differences between the two monitors are significant ($p < 0.05$).

In Fig. 7 the pointwise difference curves measured with disklike objects and those with nodular ones are shown. Note in Fig. 7 that when measured with nodular object the 95% credible intervals (the shaded area) of the pointwise differ-

ence curve at all background levels were mostly above zero, whereas the 95% credible intervals of the pointwise difference curve were above zero only at the brighter background levels when measured with disklike objects. In other words, contrast thresholds measured with nodular object demonstrated more obvious differences between the qualities of the color monitor to those of the monochrome.

FIG. 5. Contrast thresholds of the medical-grade monochrome monitor for circular objects with sharp and fuzzy edges. The C-D curves at the various luminance levels demonstrate the contrast threshold's dependency on object type. The plots also reveal that using disklike objects results in a lower (better) contrast resolution than using nodular objects. In all the plots, the contrast thresholds for the nodular targets have been adjusted by a factor of $2/3$ to account for the effective intensity-area product differences between the two object types (see Sec. IV).

IV. DISCUSSION

The results in this study have clearly demonstrated that for a given object size, a nodular object requires a higher contrast than a circular object to be visible independent of the background luminance level. There are two main contributing factors to the differences in contrast threshold for the

disklike and the nodular object. One is that the intensity profiles of the two object types differ. More specifically, in the C-D curves of this study, the contrast thresholds were represented as the maximum intensity (in pixel value) of the object relative to the background level. For the disklike object, the line profile of intensity is a step function; therefore, rep-

FIG. 6. Contrast thresholds plotted as a function of the background luminance level for the color and monochrome monitors. The background luminance level corresponds to the areas surrounding the object and is represented by their input pixel value. Thresholds measured with disklike and nodular objects are both shown. Note the relative invariance of contrast thresholds for the DICOM-calibrated medical-grade monitor over the entire luminance range indicating the realization of contrast sensitivity equalization by the DICOM LUT.

representing the contrast threshold as the pixel value difference between the object and its uniform background is appropriate. For the nodular object, however, the intensity profile varies spherically across the nodule diameter, so using the maximum intensity pixel value overestimates the relative contrast between the nodular object and its background. A more reasonable basis on which to compare the contrast thresholds of these two object types would be the integrated intensity-area product of the two profile functions since the detection threshold of low-contrast object for human visual system is determined by the total energy of the number of photons that cause an excitation of the photoreceptors in the retina. For the step function, the integrated intensity-area product would be the maximum intensity times the pixel area of the disk, $P = I_{\max} \pi R^2$, where R is the radius of the disk and $I_{\max}$ is the pixel intensity difference between the disk and its background.

For the nodular object, the intensity profile has a spherically varying intensity across the object's diameter, scaled by the maximum intensity $I_{\max}$. At the edges of the sphere the intensity would be equal to the background, and at the center

the intensity would be $I_{\max}$. All values in between would be proportional to the vertical dimension of the sphere, simulating the attenuation intensity profile of a spherical nodule (Fig. 1). The equation below demonstrates such relationship;

$$I(x, y) = \frac{I_{\max}}{R} \sqrt{R^2 - (x^2 + y^2)}. \quad (1)$$

Thus the integrated intensity-area product for the nodular object will be $P = I_{\max} \frac{2}{3} \pi R^2$. Consequently the ratio of the integrated intensity-area product for the nodular object to that of the disklike object of the same diameter is $2/3$ given the same maximum intensity $I_{\max}$. Therefore, for the same size object and the same maximum intensity, the nodular object has $2/3$ the integrated intensity-area product value or *equivalent* contrast of the disklike object. In other words, to achieve the same "equivalent contrast," the spherical nodule requires higher peak pixel intensity than the circular object and spherical nodules should have a contrast threshold 1.5 times higher than that of circular objects if everything else is equal. If the difference in the intensity-area product is the

FIG. 7. Pointwise difference curves between the medical-grade monitor and the color monitor together with the 95% credible intervals at various background luminance levels. [(a), (c), (e), (g), and (i)] The plots on the left are measured with disklike objects and [(b), (d), (f), (h), and (j)] those on the right are for nodules. Note that at all background levels and object sizes, measurements using nodular object, demonstrate more obvious differences between the two monitors, indicating that using nodular object is more sensitive in differentiating the qualities of the color monitor to those of the monochrome.

sole determining factor for the differences between the two objects' contrast thresholds, multiplying the disklike object's contrast threshold by 1.5 should theoretically map the disklike object's C-D curve to the spherical nodule's C-D curve in our measurements. However, as can be seen in the measurement results (Fig. 5), the measured contrast threshold for the spherical nodules is still larger than 1.5 times the threshold of the circular object, indicating that there are other factors contributing to the differences in the contrast thresholds of these two object types. We believe edge detection by the human visual systems may be one such factor; the sharp edges of the circular object enhance the eye's ability to detect it and may affect the contrast threshold in a more complicated manner than a mere linear relationship to the object's integrated intensity-area product.

Prior to this study, few studies had compared the contrast threshold differences of these two types of targets in today's digital display systems. Experiments in this study measured the contrast threshold differences due to object shape and have verified the appropriateness of using the nodular target types in monitor quality assessment. The results of this study also show that nodular objects are indeed more sensitive in differentiating the quality differences in DIDS than disklike objects (as they are currently being used). Therefore, nodular objects may be a better choice for routine QC of DIDS. Furthermore, it is probably better to use targets that closely resemble clinical findings and the nodular object tested here has a more clinically relevant shape than the disklike or square objects that are used in today's QC methods.

It should also be noted that during our experiments objects were more easily identified when the eye happened to be focused on the region where the object first "appeared" as opposed to when the observer had to search the screen for the object. This effect was more prominent when the target size was smaller. This effect is probably due to the temporal sensitivity of the human visual system, the topic and analysis of such effects being beyond the scope of the current study. The small objects were particularly difficult to find on the screen with spatial or temporal noise, or when the monitor surface was dirty. In addition, ambient lighting in the room contributes to the reduction in the visibility of objects. All these factors may account for some of the variability in the contrast measurements in our study. Incidentally, these factors also affect contrast sensitivity and, thus radiologists' ability to detect subtle clinical findings. Therefore, the reduction in display quality due to these factors should be tested when regular QC is performed.

Our experiment has shown that the minimum resolvable contrast threshold for nodular targets is approximately a three-pixel value difference from its background (at the center of the nodule) over the entire luminance range while using a DICOM-calibrated medical-grade monitor. This difference translates to about 1% of the dynamic range for an 8 bit image display device. It is also possibly the best achievable contrast resolution for objects with fuzzy edges in clinical images such as lung nodules and masses using DIDS simply because we measured in a uniform background, which made the "searching and detection" task much easier than it is in

clinical imaging, where pathological conditions frequently are hidden behind anatomical structures ("structural noise"), and thus may require a higher contrast threshold for detection. Our findings may have revealed the lower limit for an average human viewer using today's medical image display devices for the projection of a spherical nodule without the help of imaging processing tools such as edge enhancement schemes or computer aided diagnosis (CAD) tools. This fact may have important implications, guiding us to determine the minimum detectable contrast in medical images for pathological conditions in the digital image display environment.

The experimental results (as shown in Fig. 6) also clearly demonstrated the consequences of DICOM LUT calibration and contrast sensitivity equalization at all luminance levels and the latter's effects on low-contrast object detectability. To the best of our knowledge, this is the first experimental demonstration of the consequences of DICOM LUT calibration on actual object detectability in terms of the contrast thresholds of both disklike and nodular objects. As our results clearly show the DICOM-calibrated medical-grade monitor had nearly equal contrast sensitivity over the entire luminance range, while the uncalibrated consumer-grade monitor had an unequal and variable distribution of contrast sensitivity over the luminance range it spans. Our results also corroborated the generally acknowledged fact that consumer-grade color monitors usually have better contrast sensitivity in the darker luminance range (i.e., as in the lung field of a chest x-ray image) than in the brighter range (i.e., as in the mediumsternum area). This phenomenon is due to the LUT settings of the consumer-grade monitors. Thus, we have demonstrated unequivocally the inadequacy of these consumer-grade monitors as a primary means of rendering diagnoses based on radiographic images.

Our study is limited by the small number of monitors we tested. It is possible that other consumer-grade monitors may have higher contrast sensitivity than the one we studied. However, the primary goal of this study was not to compare the sensitivity of the consumer-grade monitor with that of the medical-grade ones. Rather, it was to study the differences in contrast thresholds of different object types and the implications for the selection of object type in monitor QC. Additionally, the quality differences between consumer- and medical-grade monitors have already been established by many others and us.^{17,39,40} We included the consumer-grade monitor in this study to demonstrate the relative sensitivity of nodular and disklike objects in differentiating quality differences and to demonstrate the effect of DICOM calibration on the contrast sensitivity over the luminance range that the monitors span. Another limitation of this study was the small number of human observers included; we hope to expand and refine our results in follow-up studies with a larger pool of human observers.

Finally, we fully realize that the detection of lesions (or targets) in real clinical images is a much more complicated task than detecting artificial targets against a uniform background, as was done in the experiments reported here. And the differences in qualities of medical image display devices

revealed by the QC measurements may not translate into clinically significant differences in diagnosis quality. However, the goal of monitor QC is to find a sensitive and practical measure that can detect subtle deterioration in monitor quality over time. It is reasonable to believe that if the DIDS is sensitive enough to enable the detection of these simulated objects in uniform backgrounds, the information loss in the image display process is minimized and these display systems are adequate for clinical diagnosis.

V. CONCLUSION

There are clear differences in contrast thresholds measured with nodular and disklike objects. The differences in contrast thresholds between the consumer-grade monitor and the medical-grade monitor are more obviously differentiated using nodular objects. Since the nodular object more closely simulates clinical findings, such as the lung nodules in chest radiography and breast masses in mammography, it may be a better and more sensitive tool for the assessment of DIDS quality. Therefore, nodular objects should be used in the QC process instead of objects with sharp edges.

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