Display systems for Digital Pathology: what are proper luminance, contrast and resolution settings?

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ABSTRACT

The past few years digital pathology has been widely adopted. The display system is a crucial component in the overall digital pathology system, since pathologists decide based upon images visualized on the display. Quality of the display can influence clinical performance, but also workflow efficiency and ergonomics.

Performance of radiology display systems has been extensively studied, and this resulted into standardization and clear requirements and guidelines. Digital pathology images and viewing conditions are very different compared to radiology. Fewer effort has gone in understanding what makes a digital pathology display fit for use, and there is no consensus yet in the digital pathology community about ideal specifications for digital pathology displays.

This paper studies specific characteristics of digital pathology display systems, such as luminance, contrast and resolution. Effects of these characteristics on visibility of relevant pathological features is described, and recommendations are made for clinically meaningful levels of luminance, contrast and resolution.

Keywords: Digital pathology, display, visualization, observer, workflow, viewing conditions.

1. INTRODUCTION

Pathology is the study and the diagnosis of diseases and is founded on the visual interpretation of features captured in images. These images could be viewed through a microscope from specimens on glass slides or, more recently, tissue slides themselves being scanned and turned into digital images that are analyzed on a display[1]. Digital Pathology has been widely adopted over the past few years as they provide multiple advantages over its predecessor. Digital Pathology allows users to compare slides under differing lighting conditions, view multiple layers and depths within a single sample, and compare potential pathologies with known pathologies on record. Slides can be reviewed at any time and in any format, at different magnifications and using a variety of stains. They can be shared in real-time between local hospitals, physicians etc., bridging the physical distance barrier. Despite this, Digital Pathology does come with its fair share of challenges as well. The requirement of certain IT infrastructure to handle such data, regulatory and privacy concerns for patient data, questions of cost-efficacy among others[2].

The benefits seem to outweigh the challenges with more and more pathologists and hospitals turning towards Digital pathology. As mentioned, one of the challenges was the requirement of IT infrastructure. The display system is a crucial component in the overall digital pathology system, since pathologists decide based upon images visualized on the display. Quality of the display can influence clinical performance, but also workflow efficiency and ergonomics. Displays can be broadly categorized into Medical Grade (MG) displays, Consumer off the shelf (COTS) displays, and Professional Grade (PG) displays[3]. In some cases, COTS displays are what is being used since this is what the company/hospital equips the staff with. They are affordable but are very limited in terms of their calibration options. PG and MG displays on the other

hand are more expensive but are more geared towards the nature of the content to be viewed and they have a longer lifetime. MG displays tend to allow for various calibration options from the luminance, colour, contrast etc, to adapt to the images on the screen. In the case of radiology and pathology images there are several display system requirements to be met to successfully display an image. Color calibration of displays for medical applications is necessary to guarantee stability of display systems over time and to ensure similar behavior between different display brands and types. Some studies[4] indicate calibration results in significant improvement in practitioner efficiency. In fact, the grayscale Digital Imaging and Communications in Medicine (DICOM)[5] Grayscale Standard Display Function (GSDF)[6] was defined exactly for this purpose.

The DICOM GSDF[6] was developed to provide an objective, quantitative mechanism for mapping digital image values into a given range of luminance values in order to produce better visual consistency in the way images appear on diverse display devices. The relationship between digital image values and displayed luminance, as defined by the GSDF, is based upon measurements and models of the human perceptual system over a wide range of luminance values. This allows the user to better calibrate the device for more accurate viewing and one which stays constant across various displays.

Looking at other display characteristics we see that in literature the performance of radiology display systems has been extensively studied, and this has resulted into standardization[4] and clear requirements and guidelines. Digital pathology images and viewing conditions are very different compared to radiology. Less effort has gone in understanding what makes a digital pathology display fit for use, and there is no consensus yet in the digital pathology community about ideal specifications for digital pathology displays.

Understanding the necessary display characteristics is also required in the Virtual Clinical Trial (VCT)[7] landscape as the modelling of displays, as well as the ability to discern features in an image are useful to the medical imaging VCT process. This is also true in the case of VCT-Derma[8,9] which looks to model the dermatology pipeline, where the visibility of high frequency signals in an image is crucial to a successful diagnosis.

This paper studies specific characteristics of digital pathology display systems, such as luminance, contrast and resolution. The effects of these characteristics on visibility of relevant pathological features is described, and recommendations are made for clinically meaningful levels of luminance, contrast and resolution.

2. METHODOLOGY

Proper characterization of display performance requires taking into account actual viewing conditions[10,11]. Contrary to radiology displays, digital pathology images are often read in office conditions[12] where ambient light typically is in the range 300-500 lux. Part (typically 1-3%) of this ambient light is reflected by the display surface. This results into reduction of effective display contrast as the reflected light is added to the light emitted by the display itself. Calculations and measurements can quantify this effect for a range of display luminance levels (250-1000 cd/m²), display contrast levels (500:1 – 1500:1) and ambient light levels (0 – 1000 lux). With the help of image processing and software tools[13] , we are capable of generated simulated display images that make visible how these display characteristics influence visualization of digital pathology images.

A more refined method analyzes visibility of clinically relevant features in digital pathology images. Several human vision models have been described in literature that can predict visibility of image features (e.g. CSF model of Barten[14], DeltaE2000[15], Just-Noticeable Difference (JND)[16]...). We use the JND model as basis, while also referring to the Barten CSF model which has been used extensively for defining calibration methods in radiology applications.

Just-Noticeable Difference is the luminance difference of a given target under given viewing conditions that the average human observer can perceive. The DICOM GSDF takes the JND index as an input to calculate the luminance[6] where one

step in the JND index results in a luminance difference that is a Just-Noticeable Difference. DICOM GSDF also allows us to apply the inverse of the formula to a device with a specific range of L values, giving us the JND index.

Equation 1 - JND index calculation from DICOM GDSF[6]

$$j(L) = A + B \times \log_{10}(L) + C \times (\log_{10}(L))^2 + D \times (\log_{10}(L))^3 + E \times (\log_{10}(L))^4 + F \times (\log_{10}(L))^5 + G \times (\log_{10}(L))^6 + H \times (\log_{10}(L))^7 + I \times (\log_{10}(L))^8$$

This can be seen in equation 1 where $\log_{10}$ represents logarithm to the base 10, j is the Just-Noticeable Difference index as a function of Luminance (L), and A = 71.498068, B = 94.593053, C = 41.912053, D = 9.8247004, E = 0.28175407, F = -1.1878455, G = -0.18014349, H = 0.14710899, I = - 0.017046845.

JND contrast maps can be generated for images, where the average JND step is calculated between each individual pixel and the average of its four neighbors. The higher the value, the brighter the pixel on the map (refer figure 1). This serves as a good visual example of high frequency signals within the image.

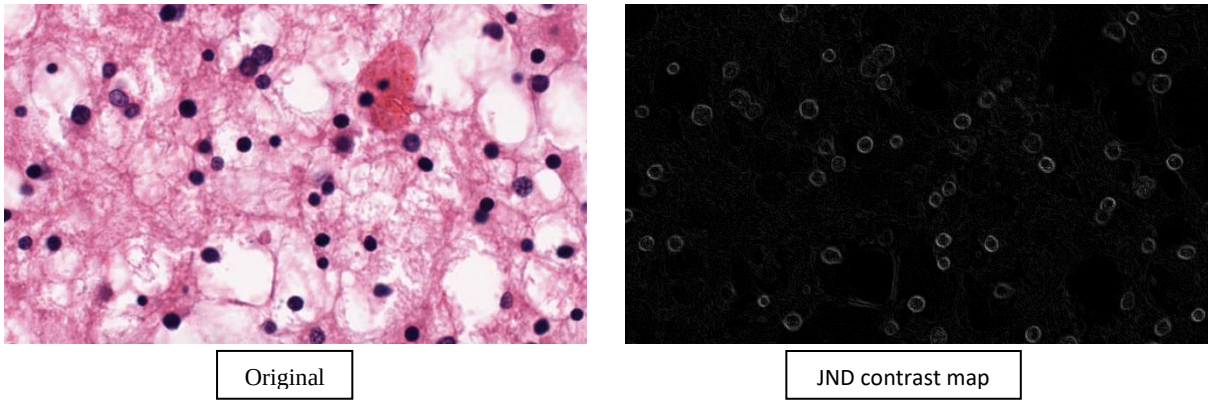

Figure 1 - A pathology image and its corresponding calculated JND contrast map

Spatial frequency content of clinical digital pathology images has also been analyzed, specifically for areas where clinically relevant features are present. Display size, viewing distance as well as image zoom levels have been taken into account. For the purpose of this manuscript a 27" pathology display[17] is used as reference for the calculations in the next section. A relevant observation is that spatial frequency content of digital pathology images is very different compared to radiology images. Barten's CSF model (refer Figure 2) was also employed to analyze the perception threshold of the clinically relevant features, and this for a range of display luminance levels, display contrast levels and ambient light conditions.

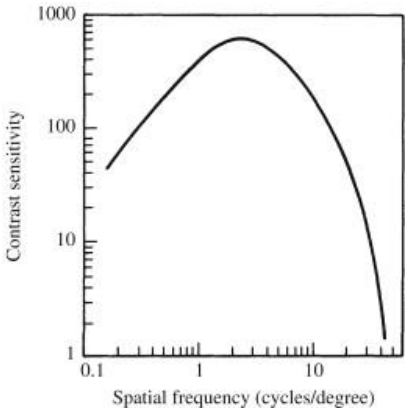

Figure 2 - Contrast Sensitivity function of the human eye[18]

Refer Figure 3 for examples of the pathology images utilized, that have been sourced from literature[19]. These images have been selected as they depict a diverse group of features. We have nuclei, blood vessels, as well as cells resulting in a lymphocytic infiltrate. For the purpose of this manuscript emphasis is laid on the image depicting nuclei.

(a)

(b)

(c)

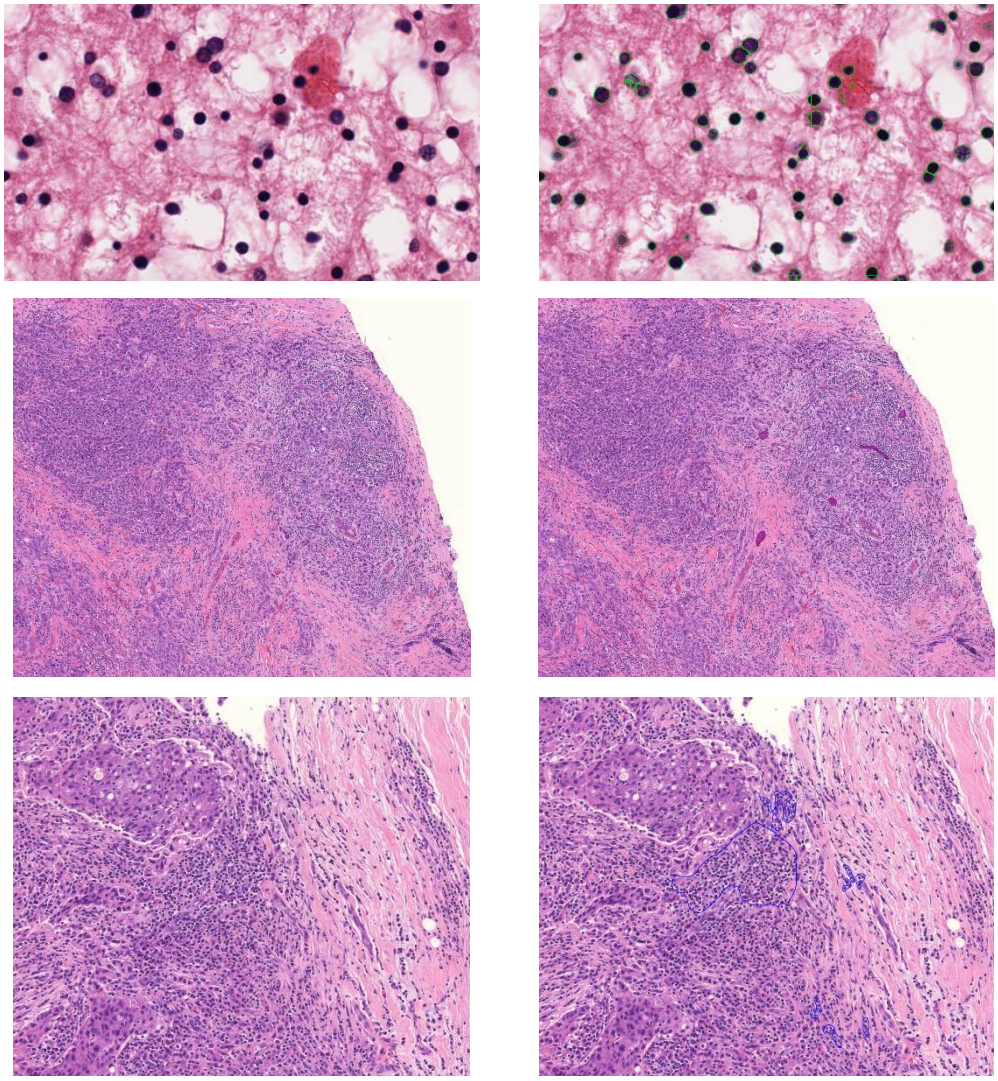

Figure 3 - Pathology images (left) and their annotated versions (right) depicting (a) cells/nuclei, (b) blood vessels, and (c) a lymphocytic infiltrate.

3. RESULTS AND DISCUSSION

We have performed experiments to analyze the influence of display luminance, display contrast ratio, and the effect of ambient light on the digital pathology images in Figure 3. Display luminance was varied from 250cd/m^2 to 1000 cd/m^2. Display contrast ratio was varied from 500:1 to 1500:1. Finally the ambient light was also varied from 0 to 1000 lux in intervals of 200 lux. Figure 4 shows examples of some of these experiments. We can see simulated display images of varying display contrast (500:1, 1000:1, and 1500:1) at ambient light of 0 lux and display luminance of 1000 cd/m^2. The images of varying ambient light (0 lux, 400 lux, 1000 lux) at fixed display contrast of 1000:1 and fixed display luminance of 500 cd/m^2. Finally, we see images of varying display luminance (250, 500, and 1000 cd/m^2) at fixed ambient light of 400 lux and fixed display contrast of 1000:1. We notice that there is little discernible change among the images of varying display contrast and the images of varying ambient light. Larger visible differences are visible when changing display brightness.

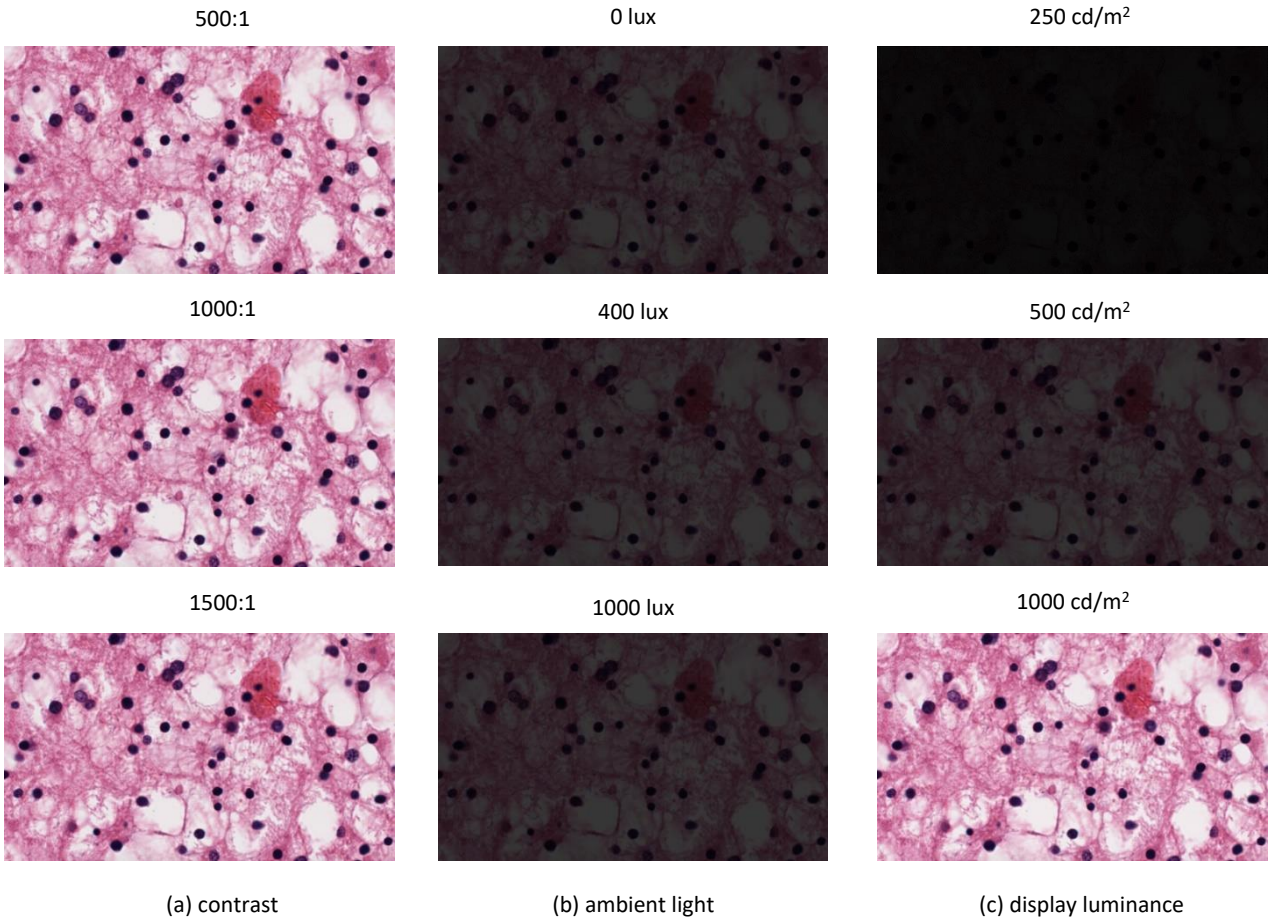

Figure 4 - Simulated Images at varying display configurations: (a) varying contrast (at 0 lux ambient and 1000 cd/m² display luminance), (b), varying ambient light (at display contrast 1000:1 and display luminance 500 cd/m²), (c) varying display luminance (at ambient light 400 lux and display contrast of 1000:1)

JND contrast maps were generated, as discussed earlier, at the various configurations of contrast, display luminance and ambient light. JND ranges were plotted as a function of the ambient light for the varying contrasts (solid, dotted lines) and for varying display luminance (different colored lines). Analyzing the graph in Figure 5 we see that ambient light has a large negative effect on the available JND range of a display (and therefore on perceived contrast and visibility of image features). For the different display brightness and display contrast settings tested, there is on average a 35% reduction in JND range when ambient light is at 1000 lux compared to 0 lux. Another observation is that the higher the display brightness is, the larger the available JND range of the display. This effect is remarkably strong, as a display with brightness 1000 cd/m² has approximately 25% higher JND range than a display with brightness 250 cd/m². A final learning from Figure 5 is that the effect of display contrast is much smaller than the effect of both ambient light and display brightness. There is little difference in display JND range when varying contrast between 500:1 and 1000:1, and this effect is even smaller at higher ambient light levels.

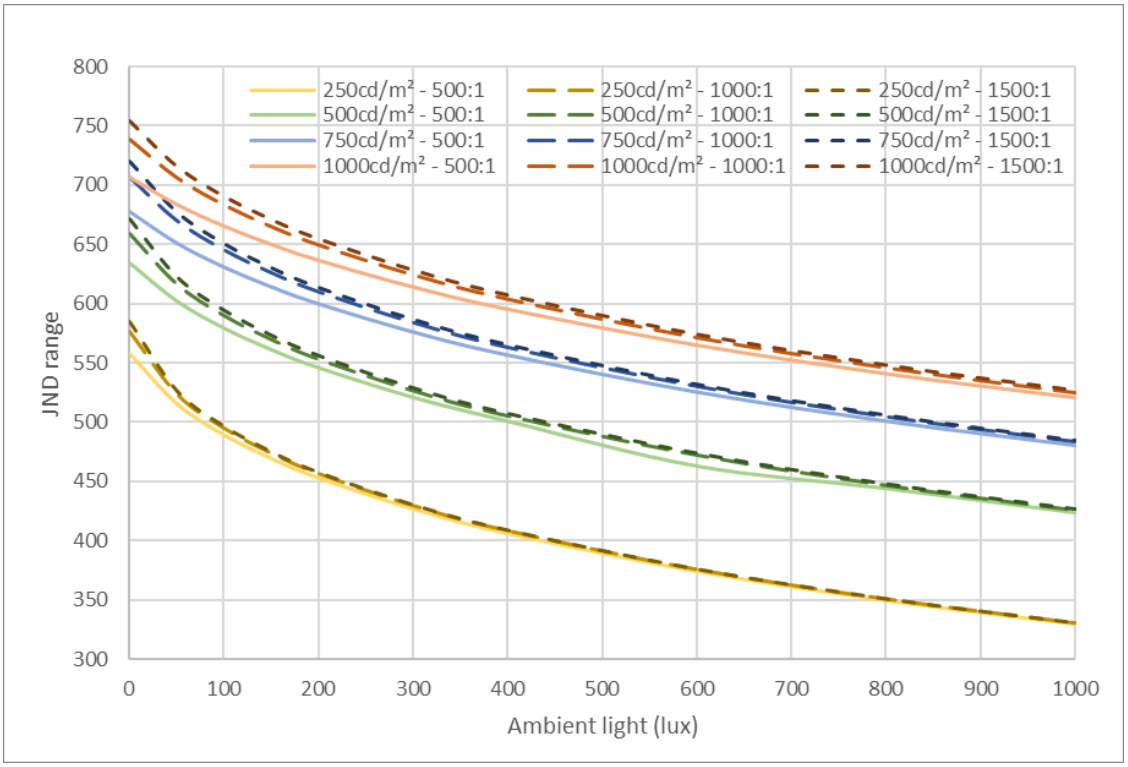

Figure 5 - Effect of ambient light on the display JND range for different display luminance and display contrast values

Figure 6 shows the effect of display luminance on the detectability of clinically relevant features. These small features correspond to higher frequency signals in the image, and this is also seen from the Fourier transform image of these features. It is also noticed that display luminance values beyond 350 cd/m² (up to 1000 cd/m² or higher) are beneficial particularly for visibility of small details in digital slide images (Figure 6 (b)). Typical viewing strategies of digital pathology images makes extensive use of pan and zoom operations. Often the full slide is first inspected at low magnification levels, and when a clinically relevant area is detected then that area is inspected in detail at higher zoom levels. Higher display luminance increases visibility of subtle, smaller features. Therefore, using a display with higher display luminance may reduce the need for panning and zooming actions, thereby reducing reading time.

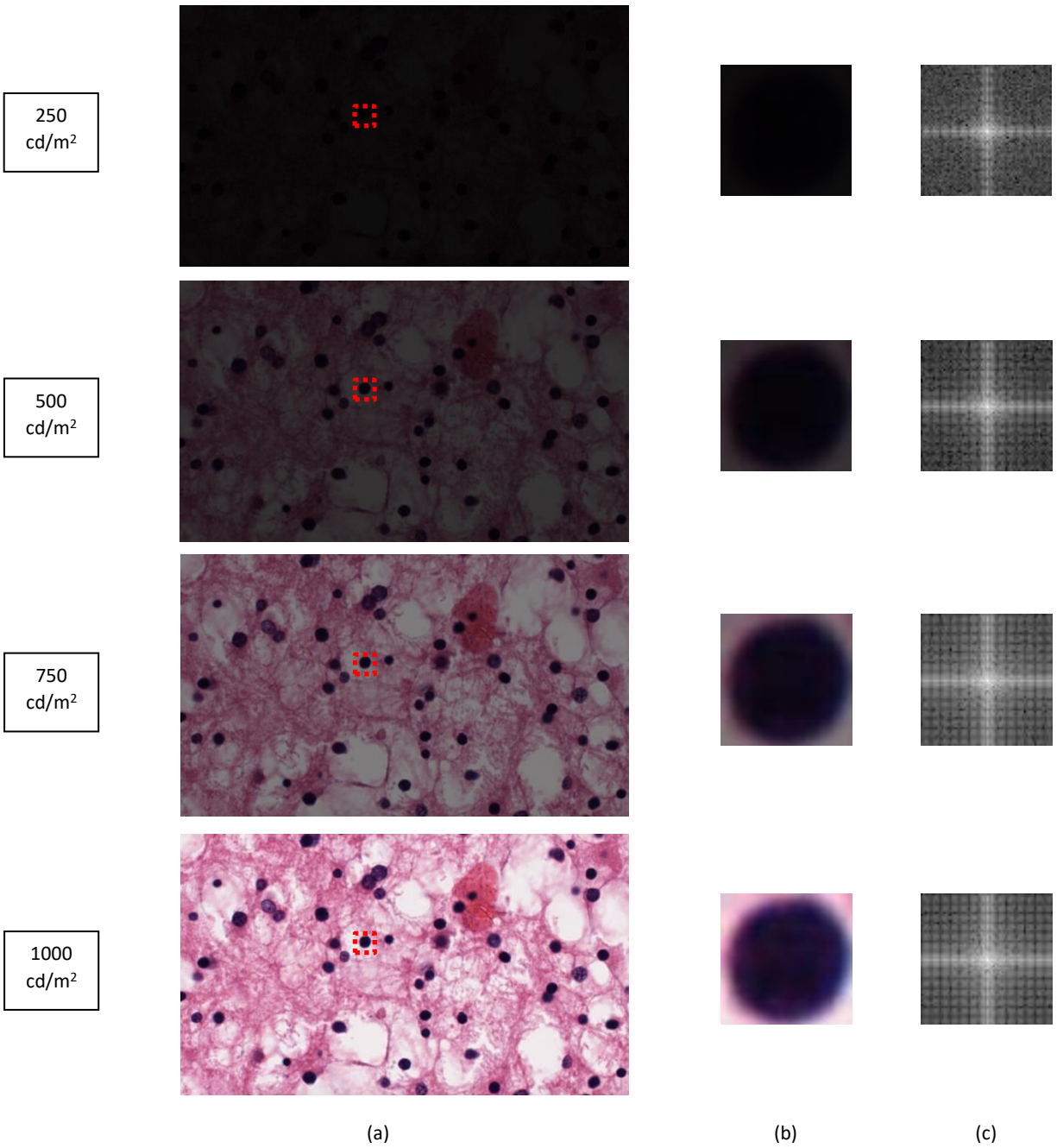

Figure 6 - Varying the display luminance from 250 cd/m^2 to 1000 cd/m^2 at constant contrast (1000:1) and ambient light (400lux) (a) Resulting images for each display luminance with a feature highlighted for reference, (b) Zoomed in view of the feature highlighted in (a), (c) Fourier transform of image (b) depicting the spatial frequency contents of the specific feature.

Calculations were performed with the assumption that digital pathology images are visualized on a display of typical size (27") (eg. Barco MDPI-8127)[17] and normal viewing distance (approx. 65cm). Calculating the cycles per degree of visual angle with these measurements results in 1˚ corresponding to 1.13458cm on the screen. Any change in the viewing distance will result in a change in the area covered by our viewing angle while also, any change in zoom factor changes the spatial frequency content (figure 7).

For a Barco MDPI-8127 display, the pixel pitch is around 0.155mm. Using this we can see that there would be approx. 73.2 pixels within the 1 degree of visual angle. It takes 2 pixels (one on and one off) for one sine cycle so with this we can safely assume that 1 degree of visual angle corresponds to approx. 36.6 cycles. Analyzing the images in figure 3 we can estimate what spatial frequency range corresponds to some of the clinically relevant features. For lymphocytic infiltrate cells, we have a size of around 2-3.5 cycles for an individual cell which corresponds to a range of 18.3-10.4 cycles per degree (cpd). For blood vessels we see a size of around 49 cycles length wise but around 2.5 cycles width wise corresponding to a range of .75 cpd lengthwise and 14.6 cpd width wise. For the nuclei we see a size of around 25 cycles, though the edges are around 1-2 cycles corresponding to 1.46 cpd, while the edges correspond to 18.3 cpd onwards.

In reality of course a feature has a broad range of corresponding spatial frequencies. These estimates are just intended to get a feeling of the relevant spatial frequency range that corresponds to the relevant features. These calculations have been performed when zoomed into the relevant feature. It is important to notice that some of these clinically relevant features correspond to fairly high spatial frequency contents (eg. > 10 cpd) which means that they are at the limit of what the human eye can perceive. That explains why panning and zooming is often performed when viewing digital pathology images, as zooming in on a feature corresponds to lowering the spatial frequency contents, and therefore making it easier to perceive. Based on Barten's work on contrast sensitivity functions, we also know that increasing brightness has a positive effect on detectability, and this is particularly the case for higher spatial frequencies (> 10 cpd). That explains why it is easier to see subtle small details in digital pathology images on a display with higher display brightness.

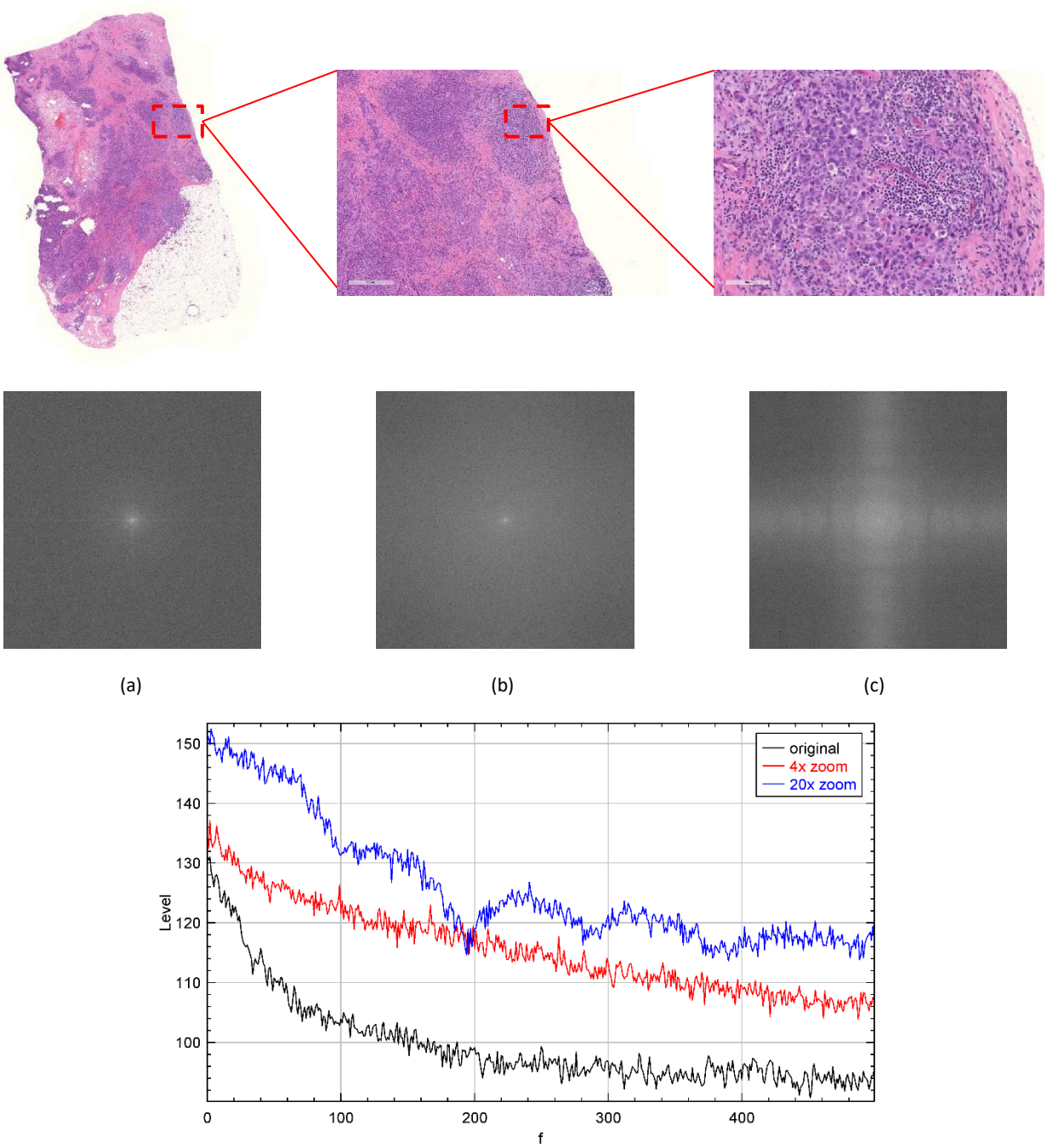

Figure 7 - Example showing change in zoom factor from (a) original image-no zoom, (b) 4x zoom, and (c) 20x zoom, as well as the spatial frequency plots. The horizontal profile (information contents in the image in function of horizontal spatial frequency) is also seen here.

Based on all results obtained, we observe that in case of higher ambient light levels, display luminance is more important than display contrast in order to achieve sufficient JND range and ability to perceive subtle image details. From the images in figure 4 we can see that a display brightness of 500 cd/m² or more largely increases JND range and visibility of image

details. A minimum display brightness of 350cd/m^2 seems to achieve a sufficient JND at normal office ambient light conditions, although higher display brightness will clearly contribute to better visibility of image details.

4. CONCLUSIONS

This paper studied specific characteristics of digital pathology display systems, such as luminance, contrast and resolution. Effects of these characteristics on visibility of relevant pathological features has been described, and actionable recommendations have been made for clinically meaningful levels of display luminance, contrast and resolution.

At higher ambient light levels (typical for digital pathology reading conditions) display luminance has more influence on perceived image quality and feature detectability than display contrast. Results suggest a minimum display contrast of 1000:1 and a minimum display luminance of 350 cd/m² (or higher) in order to achieve sufficient perceived contrast at normal office ambient light conditions. Also, results suggest that a display with higher luminance may reduce the need for zoom and panning actions, as smaller clinically relevant features will be visible at lower zoom levels.

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