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IMAGE DISTORTION, SPATIAL RESOLUTION, AND SEGMENTATION CAPABILITIES OF THE i-CAT FLX CONE-BEAM COMPUTED TOMOGRAPHY MACHINE

by

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Submitted in partial fulfillment of the requirements for the degree of Master of Science in Dentistry

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IMAGE DISTORTION, SPATIAL RESOLUTION, AND

SEGMENTATION CAPABILITIES OF THE i-CAT FLX

CONE-BEAM COMPUTED TOMOGRAPHY MACHINE

Abstract

By

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Background: The orthodontic community has been searching for three-dimensional (3-D) visualization to improve diagnosis. The invention of cone-beam computed tomography (CBCT) provided the 3-D image at the cost of high radiation exposure. Marketing campaigns claim that a 3-D scan can now be completed with less radiation than a digital panoramic radiograph. Before routine use of CBCT is adopted, the remaining unknown is the diagnostic quality of the images.

Purpose: The main objective was to evaluate images produced by a commercially available CBCT machine (i-CAT FLX, Imaging Sciences International, Hatfield, PA) for measurement accuracy and spatial resolution.

Research Design: Images from two phantoms were obtained at different settings. Computer software measurements were compared to the direct measurements. In addition, thirty volunteers evaluated spatial resolution via line-pair tests. Resolution criteria included distinct separation and patterns of four lines.

Results: On the first phantom, no statistically significant difference was found between the computer and direct measurements. The survey results from the second phantom yielded resolutions ranging from 0.395 mm to 0.658 mm. The lowest resolution (0.658 mm) shows a superior level of detail than that from a previous study using the same methods on a Classic i-CAT machine (0.860 mm). The best scans from each study showed approximately equivalent resolutions. A regression analysis indicated that voxel size has the greatest effect on resolution of the flexible setting options. An R^2 of 0.792 was comparable to that from a prior line-pair test evaluation (0.718).

Conclusions: At the lowest settings, the i-CAT FLX produces images that allow for clinically accurate measurements and diagnostic resolution. With new

technology and decreased radiation exposure, the lowest possible resolution outcomes provide a higher level of detail than images from an earlier machine.

Key Words: CBCT, RADIATION, IMAGE QUALITY

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INTRODUCTION

Historically, two-dimensional (2-D) radiographs were the foundation of orthodontic diagnostic records. As digital radiography evolved, the radiation exposure to the patient decreased. However, a limitation of 2-D is the necessity to order additional exposures to visualize adverse conditions such as impacted teeth and bony abnormalities. Another issue with 2-D is image distortion due to patient orientation and film to object distance.[5]

The advent of cone-beam computed tomography (CBCT) allowed the capability of capturing 2-D and three-dimensional (3-D) from one acquisition.[17] The use of CBCT is becoming more prevalent by orthodontists for routine diagnostic purposes. The major concern with this technology is the exposure of increased levels of radiation to the patient. The ALARA (as low as reasonably achievable) principle guides clinicians in the selection of diagnostic radiography. In general,

radiographs are prescribed on an individual basis, after evaluation of the clinical situation.

Recently, Imaging Sciences International, LLC released the i-CAT FLX CBCT machine with the claim that images can be produced while exposing the patient to a lower radiation dose than a 2-D panoramic radiograph. A prior study that evaluated the dosimetry of the i-CAT FLX using several exposure protocols concluded the adult average effective dose for the lowest setting is 8 microSieverts (μSv).[11] A digital panoramic radiograph exposes the patient to 14.2-24.3 μSv. A digital lateral cephalogram exposes the patient to 4.5-10.4 μSv.[14] Orthodontic diagnostic evaluation historically combined lateral cephalometric and panoramic radiographs. The possibility of capturing the radiographic information necessary for diagnosis in a single volume is appealing to practitioners.

Before widespread use is adopted, the images obtained should be evaluated for adequate diagnostic quality, which can be determined via measurement accuracy and spatial resolution. The purpose of this study is to provide criteria to support routine use of CBCT via

measurement accuracy, spatial resolution, and segmentation capabilities.

REVIEW OF LITERATURE

CBCT was initially introduced for angiography in 1982. Since the exposure fully incorporates the region of interest (ROI), only one rotation is needed to capture all of the data. Thus, CBCT scans can be taken quickly.[17]

CBCT in dentistry was introduced in 1998, and it was recommended when conventional radiography did not provide enough diagnostic information in situations including clefts, unerupted teeth, supernumeraries, root resorption, or for orthognathic surgery preparation. In theory, no difference exists in linear or angular measurements between traditional radiographs and CBCT. However, surface contour reconstructions can yield some measurement errors. All measurements should be made in the multi-planar view instead of the volume renderings and shaded surface displays. When reading CBCT, one should view the region of interest from at least two planes at right angles to each other, also viewing the volumetric renderings in 3-D and scrolling through the region of interest in 2-D planes. A major application of

CBCT in orthodontics is the evaluation of boundary conditions for tooth movement.[6]

In 2012, the American Dental Association Council on Scientific Affairs questioned whether the amount of radiation from CBCT was justified and if training for data interpretation was adequate. The basic recommendation was to decide to use CBCT only after a review of the medical history, a clinical exam, and prior imaging that warranted further investigation. Since children and adolescents are more radiosensitive, the cancer risk per unit dose of ionizing radiation is higher, plus there is a longer lifetime risk of cancer development. CBCT is only deemed necessary when it can aid in the improvement of clinical outcomes. As an essential concept, optimization means using the least amount of radiation to obtain adequate image quality. Using the smallest possible field of view for the targeted anatomical structure and thyroid collars and lead aprons when they do not interfere with the exam, help lower exposure.[16]

An August 2013 position statement by the American Academy of Oral and Maxillofacial Radiology reiterated

that orthodontists should justify the use of CBCT on an individual basis. Their guidelines for orthodontists also include the assessment of risk of radiation dose, the commitment to minimize patient exposure, and the practitioner's responsibility to maintain competency in performing and interpreting CBCT studies. In addition, creation of a CBCT protocol that restricts the field of view (FOV) to the ROI, minimizes exposure in tube current (mA) and tube voltage (kVp), and balances the resolution with adequate visualization of structures is dubbed a dose reduction protocol.[3]

Spatial resolution, the ability to visualize fine detail in an image, is often measured with line-pairs per millimeter. At least two pixels are required to resolve a line-pair, one from the radio-opacity and one from the radiolucency. The theoretical resolution is determined by the pixel size. Actual resolution is usually lower due to noise. The goal of segmentation is to reduce an image to its basic components, separating objects from the background and identifying objects of interest, this allows measurements, relative localization, and density calculations. Voxel dimensions are determined by the

pixel dimension of the detector. Thus, the voxels are isotropic, equal in all three dimensions. Basis images, which resemble lateral cephalograms, are captured in sequence. Adjustments can be made in mA, kVp, voxel size (determined by tube focal spot size), geometric configuration of x-ray, and the detector pixel size. Decreasing voxel size increases spatial resolution, but a higher amount of radiation is usually required to decrease the voxel size. CBCT can expose the patient to 52 to 1025 μSv depending on the type and model of CBCT. These are similar to 4 to 77 digital panoramic images at 13.3 μSv. Radiation is decreased by beam collimation, chin elevation, and thyroid/cervical spine shielding. CBCT provides the capability of yielding 2-D and 3-D in a single acquisition.[17]

In 2012, the Journal of the World Federation of Orthodontists published about the myths and facts of CBCT. They stated that CBCT has higher levels of radiation than panoramic and cephalometric radiographs but less than a medical computed tomography, based on the range of 20-1025 μSv. Also, natural background radiation is 8 μSv per day, but the acute nature of the radiation

from CBCT does not promote cellular repair mechanisms as continuous low level radiation does. Thus, CBCT is not justified if it is only being used to construct a panoramic and cephalometric view. CBCT requires computer software to reformat images and volume render, and not all software systems are built to handle the same degree of accuracy. The volume rendering can produce false negative or false positives for determining external root resorption. The practitioner should scroll through the slices to view images from all three axes.[1]

Prior studies have computed modulation transfer functions to characterize spatial response of an imaging system. Kwan, et al. showed the image quality decays radially from the axis of rotation as calculated from a line-spread function.[7] Spatial resolution depends on the location within the field of view. The modulation transfer function analysis was highest at the median level and center of rotation.[12] Since image noise limits the visibility of low-contrast structures, contrast-to-noise ratios are used to provide greater clarity.[10]

Line-pair tests have been conducted in several other studies. Since CBCT devices are useful for visualizing

high contrast structures, the visualization of low contrast structures is achieved by changing the exposure settings. Selection of flexible settings is based on the needs of the case as determined by the dental professional.[13]

Quality assurance can be determined by using automated phantoms. Clinical personnel should know how to assess the quality of their machines on a regular basis. These phantoms can measure uniformity, noise, contrast linearity, geometric accuracy, low-contrast resolution, and spatial resolution. The phantom sensors should be placed peripherally and centrally. Modulation transfer function is used to measure spatial resolution by locating the pixel with the maximum value of three adjacent slices.[15]

In another study, the filter and kVp did not affect overall image quality. Images at lower mA showed adequate diagnostic quality. There was no difference in image quality with changes in settings of the CBCT machine. Voxel size, mA, and image quality are closely related. High resolution does not always mean high image quality.[8]

Bryant, et al. studied scan uniformity of the i-CAT. Mass outside the slice, termed the exo-mass effect, altered the readings. The central part of the scan appeared relatively constant. When a slice contained a mass of five grams, the i-CAT measures the correct volume. Since a 0.4 millimeter (mm) slice of an adult head is seven grams, the i-CAT scan appeared darker.[2]

Linear measurements were seen to be accurate between the Galileos CBCT by Sirona and soft tissue cadaver specimens. Measured point-to-point distances of gutta purcha markers showed high accuracy.[4] The i-CAT Next Generation scans were taken at extended field of view 17x23 centimeter (cm) with 0.3 mm voxel size and radiation of 36-74 μSv. No difference between CBCT and craniometric measurements were found. All cephalometric measurements were different from their craniometric counterparts with a mean difference of 5 mm. Thus, the 2-D normalized values should not be used for CBCT.[5]

The NewTom 3G CBCT machine provides a one-to-one image to reality ratio. To test this claim, a mandible with titanium markers was placed in an acrylic box simulating soft tissue. Intra-reliability of

measurements ranged from 0.977 to 1.000. Thus, projection errors of traditional cephalometrics and positioning errors are eliminated through the use of CBCT.[9]

Based on the current literature, the use of CBCT in orthodontics is still under debate. The major argument against routine CBCT use is increased radiation exposure to obtain adequate image quality. The purpose of this study is to evaluate the image quality of scans taken at the machine settings that allow the lowest possible radiation exposure. The significance of this data has the potential to change the trend towards 3-D imaging.

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STATEMENT OF THESIS

The i-CAT FLX cone-beam computed tomography (CBCT) machine is advertised for less radiation exposure than a panoramic image. Before widespread use is adopted, the images obtained should be evaluated for adequate diagnostic quality. Diagnostic quality can be determined via measurement accuracy and spatial resolution. The purpose of this study is to provide criteria to support routine use of CBCT via measurement accuracy, spatial resolution, and segmentation capabilities.

One hypothesis tested if there are significant differences between measurements of scans from the i-CAT FLX and measurements made directly on the CIC phantom. The second hypothesis evaluated if there is a significant difference in spatial resolution as settings are changed.

IMAGE QUALITY, SPATIAL RESOLUTION, AND MEASUREMENT ACCURACY OF THE i-CAT FLX

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ABSTRACT

Title: Image quality, spatial resolution, and measurement accuracy of the i-CAT FLX.

Article Type: Original article

Key words: CBCT, RADIATION, IMAGE QUALITY

Background: The orthodontic community has been searching for three-dimensional (3-D) visualization to improve diagnosis. The invention of cone-beam computed tomography (CBCT) provided the 3-D image at the cost of high radiation exposure. Before routine use of CBCT is adopted, the remaining unknown is the diagnostic quality of the images.

Purpose: The main objective was to evaluate images produced by a commercially available CBCT machine (i-CAT FLX, Imaging Sciences International, Hatfield, PA) for measurement accuracy and spatial resolution.

Research Design: Images from two phantoms were obtained at different settings. Computer software measurements were compared to the direct measurements. Thirty volunteers evaluated spatial resolution via line-pair tests. Resolution criteria included distinct separation and patterns of four lines.

Results: On the first phantom, no statistically significant difference was found between the computer and direct measurements. The survey results from the second phantom yielded resolutions ranging from 0.395

millimeters (mm) to 0.658 mm. The lowest resolution (0.658 mm) shows a superior level of detail than that from a previous study using the same methods on a Classic i-CAT machine (0.860 mm). The best scans from each study showed approximately equivalent resolutions. A regression analysis indicated that voxel size has the greatest effect on resolution of the flexible setting options.

Conclusions: At the lowest settings, the i-CAT FLX produces images that allow for clinically accurate measurements and diagnostic resolution. With new technology and decreased radiation exposure, the lowest possible resolution outcomes provide a higher level of detail than images from an earlier machine.

INTRODUCTION

Historically, two-dimensional (2-D) radiographs were included in orthodontic diagnostic records. As digital radiography evolved, the radiation exposure to the patient decreased. However, a limitation of 2-D is the necessity to order additional exposures to visualize adverse conditions such as impacted teeth and bony abnormalities. Another issue with 2-D is image distortion due to patient orientation and film to object distance.[1]

The advent of CBCT allowed the capability of capturing 2-D and 3-D from one acquisition.[2] The use of CBCT is becoming more prevalent by orthodontists for routine diagnostic purposes. The major concern with this technology is the exposure of increased levels of radiation to the patient. The ALARA (as low as reasonably achievable) principle guides clinicians in the selection of diagnostic radiography. Prescription of radiographs is determined on an individual basis, after clinical evaluation.

Recently, Imaging Sciences International, LLC released the i-CAT FLX CBCT machine with the claim that images can be produced while exposing the patient to a lower radiation dose than a 2-D panoramic radiograph. A prior study evaluated the dosimetry of the i-CAT FLX using several exposure protocols. The adult average effective dose for the lowest setting was 8 microSieverts (μSv).[3] A digital panoramic radiograph exposes the patient to 14.2-24.3 μSv. A digital lateral cephalogram exposes the patient to 4.5-10.4 μSv.[4] Orthodontic diagnostic evaluation traditionally combined lateral cephalometric and panoramic radiographs. The possibility of capturing the radiographic information necessary for diagnosis in a single volume is appealing to practitioners.

Before widespread use is adopted, the images obtained should be evaluated for adequate diagnostic quality. Diagnostic quality can be determined via measurement accuracy and spatial resolution. The purpose of this study is to provide criteria to support routine use of CBCT via measurement accuracy, spatial resolution, and segmentation capabilities. The first hypothesis

tested if there are significant differences between measurements of scans from the i-CAT FLX and measurements made directly on the CIC phantom. The second hypothesis evaluated if there is a significant difference in spatial resolution as settings are changed.

MATERIALS AND METHODS

Two phantoms were used to determine measurement accuracy and spatial resolution of a CBCT machine called the i-CAT FLX (Imaging Sciences International, Hatfield, PA). The images were taken at the private orthodontic office of Ryan K. Tamburrino, DMD and Shalin R. Shah, DMD, MS (Center for Orthodontic Excellence, Princeton Junction, NJ). The machine is calibrated daily with a container of distilled water to match Hounsfield units with known standards. In addition, shutter and panel calibrations are conducted frequently. The phantom was placed in the machine using the laser coordinate guide system for orientation. Scout images and final images were taken using i-CAT software, and DICOM files were retrieved from the machine. Measurements were made using Dolphin Imaging software (Chatsworth, CA).

The first phantom (Craniofacial Imaging Center [CIC] phantom) was used to evaluate measurement accuracy (Figure 1). The CIC phantom is acrylic with embedded chromium spheres (Small Parts, Miami Lakes, FL). The

spheres are 0.3 mm in diameter, placed approximately five mm apart in three coordinate planes (x, y, and z) with a common intersection point. Four scans were selected of the same image size, one at each setting. Six point-to-point measurements (two axial, two sagittal, and two coronal) were conducted per scan and repeated on consecutive days by the principal investigator (ACA). The averages of these measurements were compared to averages from the direct measurements on the phantom. After image orientation, measurements for height were made in the midline sagittal slice and measurements for width and depth were made in the midline axial slice. The measurements for center-to-center distances on the actual CIC phantom were used from a prior study.[5] All computer measurements were made on two separate days for comparative purposes.

The second phantom, the C phantom (Phantom Laboratory, Salem, NY) houses a set of high-contrast metallic line-pairs embedded in acrylic. The dead space of the phantom is filled with distilled water. It contains nine series of four parallel plates placed at decreasing intervals from 0.35 to 1 mm (Figures 2, 3).

Image resolution is determined by selecting the series that shows a clear distinction between the metal plates. 14 settings were chosen for investigation (Table I). Duplicate scans were taken at four of the settings for scanner reliability, yielding a total of 18 scans. After orientation, sagittal slices were constructed for each of the 18 scans. The hard and soft tissue segmentation was adjusted to minimize noise. All images were magnified to the same degree when transferred onto slides with a black background in PowerPoint (Microsoft, Redmond, WA). Each slide was duplicated for intra-operator reliability yielding a total of 36 survey entries. The slide order was randomized using a random list generator (www.random.org). Thirty volunteers were given examples and instructions for reading the slides. Slides were viewed on a Dell UltraSharp 2007 FPB 20.1 inch LCD monitor (Dell Computer, Round Rock, TX). The evaluators were asked to determine the closest series to the screen's left that showed a clear distinction of four lines and a pattern of four lines. It was possible for these two questions to have the same answer for a given slide. The resolution was determined by averaging the two or four slides from that associated setting. A

ranking of 1 through 14 was assigned, with 1 being the best resolution.[5] The Hitachi Elvis phantom, a human skull embedded in acrylic, was also scanned at the same settings (Figure 4). This phantom shows the ability to segment and view human dentition and anatomic structures at each of the settings evaluated.

RESULTS

Computer measurements for the CIC phantom showed an excellent intra-operator reliability of 0.904. The averaged computer measurements, when compared to the original digital caliper measurements on the phantom, showed an interclass correlation of 0.986 (Table II). The 30 evaluators of the C phantom showed excellent intra-operator reliability. The reader reliability for separation of four lines was 0.820 and for a pattern of four lines was 0.884 (n=18). The scanner reliability of the duplicate scans from the i-CAT FLX were 0.861 for separation and 0.894 for pattern (n=4). The 14 image settings were evaluated by 30 volunteers without exclusions (Table III, Figure 5). The average image resolution for the separation of lines ranged from 0.395 to 0.658 mm. The 16x8 centimeter (cm), High Resolution scan was the best and the 16x13 cm, QuickScan+ showed the lowest score. The average image resolution for the identification of a pattern ranged from 0.362 to 0.593 mm with the same setting options ranking highest and lowest. The coefficient of determination (R^2) showed that voxel

size had the most effect on resolution. An R^2 of 0.792 for clear separation and 0.911 for pattern is explained by voxel size alone (Figure 6,7). Voxel size, kVp, scan time, and mA all showed significant values of $P<0.05$ (Table IV). Multivariate step-wise analysis showed that voxel size and kVp were the most predictive determinants for resolution. The combination of voxel size and kVp is 0.922 for separation and 0.944 for pattern. Image size had the least effect with 0.073 for clear separation and 0.031 for pattern recognition.

DISCUSSION

The use of CBCT for orthodontic diagnosis has been frequently debated. The most contentious point is the amount of radiation exposure to the patient. Since many of the orthodontic patients are adolescents, the risk of radiation side-effects and lifetime radiation dose is higher. For this reason, and the increased cost of the CBCT machines, many practitioners elect to include panoramic and cephalometric 2-D radiographs in their diagnostic procedures.

CBCT measurements and digital caliper measurements have been compared before. TMJ landmarks measured on an earlier generation i-CAT provided accurate reproducible measurements.[6] The fact that the intra-operator reliability and inter-class correlation between the computerized and actual measurements are very high supports the hypothesis that there is no difference between the values. Measurement accuracy of other CBCT machines was conducted with digital measurements compared to caliper measurements on a plastic skull.[7]

While there is a high level of agreement between the values, there are slight differences present. Baumgaertel, et al. described two theories of measurement error as experienced during computer and digital caliper measurements.[8] Because voxels are volumes, software measurements can be at the center of the volume while the hand measurements are at the periphery of the object. Thus, the software measurements would be smaller by the size of one voxel. The other theory is the partial volume effect, where the voxel can only hold one density even if it lies on the border of an object and space. This hybrid voxel appears as one density rather than a combination of the two.[8] If either of these theories are valid, measurements of a CBCT image could be predictably larger than the true anatomical values.

The present study accepts the null hypothesis that there is no statistically significant difference between computer measurements of scans from the i-CAT FLX and measurements made directly on the CIC phantom.

The spatial resolution data might yield to an increase in the use of CBCT for diagnosis. The average image resolution for the separation of lines ranged from

0.395 to 0.658 mm as compared to the Classic i-CAT range of 0.622 to 0.860 mm.[5] Thus, the lowest radiation scans showed resolutions in the same range as the highest radiation scans from the earlier i-CAT machine. The scans yielding these results were taken at the 16x13 cm, QuickScan+ setting, showing that all the information needed for diagnosis can be obtained from a single volume. Ballrick, et al. also found that the voxel size had the most effect on resolution in agreement with our data.[5] In 2012, Pauwels showed that there is a good correlation between voxel size and line-pair scores, supporting our findings.[9] Voxel size is a rational predictor of spatial resolution.[10]

The present study accepts the alternate hypothesis that there is a difference in spatial resolution as settings are changed. Thus, at the lowest settings, the i-CAT FLX produces images that allow for clinically accurate measurements and diagnostic resolution. There is a distinguishable higher level of detail with the i-CAT FLX than the Classic i-CAT machine. Scans at the lowest exposure settings provide adequate details for

general diagnosis. Flexibility in settings allows for extremely high levels of detail when selected.

One limitation in the use of the i-CAT FLX is the frequency of machine restarts required when taking consecutive scans. However, after each restart, the machine remembers exactly what protocol and which scout images were taken to prevent over-exposing the patient. Another limitation is that diagnostic abilities were not evaluated, and all possible settings were not included. Future studies can compare our images to that of other currently available machines. A total of 84 scans were taken and are available for future comparisons to new flexible setting machines.

CONCLUSIONS

Scans from the i-CAT FLX produced images that were able to be accurately measured and provided diagnostic spatial resolution, even at the lowest possible settings. Since these settings expose the patient to less radiation than a 2-D panoramic radiograph, low-dose 3-D scans can be approved for orthodontic diagnosis and treatment planning. The question remains if it is justified to expose patients to higher levels of radiation to gather less information.

Table I. Scanning protocols for the i-CAT FLX

Image Size (cm)	Region of Interest (ROI)	Protocol	Degrees	Voxel (mm)	kVp	mA	Exposure Time (s)
8x8	Dental	QuickScan+	180	0.4	90	3	2.0
16x6	Maxilla	QuickScan+	180	0.4	90	3	2.0
16x6	Mandible	QuickScan+	180	0.4	90	3	2.0
16x8	Both Arches*	QuickScan+	180	0.4	90	3	2.0
16x11	Arches + TMJ	QuickScan+	180	0.4	90	3	2.0
16x13	Standard Ceph	QuickScan+	180	0.4	90	3	2.0
8x8	Dental	QuickScan	180	0.3	120	5	2.0
16x6	Maxilla	QuickScan	180	0.3	120	5	2.0
16x6	Mandible	QuickScan	180	0.3	120	5	2.0
16x8	Both Arches*	QuickScan	180	0.3	120	5	2.0
16x11	Arches + TMJ	QuickScan	180	0.3	120	5	2.0
16x13	Standard Ceph	QuickScan	180	0.3	120	5	2.0
16x8	Both Arches*	Standard	360	0.3	120	5	3.7
16x8	Both Arches*	High Resolution	360	0.2	120	5	7.4

TMJ, temporomandibular joint; *ceph*, cephalometric.
* Duplicated scans.

Table II. CIC data

	CBCT measurements	Direct measurements
Mean (mm)	5.1898	5.2112
Standard deviation	0.3552	0.38967
Intra-class correlation	0.904	
Inter-class correlation	0.986	

Table III. C phantom data

Image setting	*Clear separation of 4 lines (mm)*	*Pattern of 4 lines (mm)*	*Ranking by clear separation*	*Ranking by pattern*
8x8 cm, Dental, QuickScan+	0.613 (+/- 0.049)	0.558 (+/- 0.051)	12	10
16x6 cm,Maxilla, QuickScan+	0.588 (+/- 0.073)	0.548 (+/- 0.029)	9	9
16x6 cm, Mandible, QuickScan+	0.606 (+/- 0.047)	0.563 (+/- 0.027)	11	12
16x8 cm, Both Arches, QuickScan+*	0.597 (+/- 0.042)	0.560 (+/- 0.026)	10	11
16x11 cm, Arches + TMJ, QuickScan+	0.616 (+/- 0.054)	0.565 (+/- 0.036)	13	13
16x13 cm, Standard Ceph, QuickScan+	0.658 (+/- 0.067)	0.593 (+/- 0.044)	14	14
8x8 cm, Dental, QuickScan	0.573 (+/- 0.044)	0.520 (+/- 0.057)	8	8
16x6 cm,Maxilla, QuickScan	0.548 (+/- 0.036)	0.484 (+/- 0.050)	3^	4
16x6 cm, Mandible, QuickScan	0.553 (+/- 0.040)	0.485 (+/- 0.054)	5	5^
16x8 cm, Both Arches, QuickScan*	0.543 (+/- 0.031)	0.480 (+/- 0.046)	2	3
16x11 cm, Arches + TMJ, QuickScan	0.555 (+/- 0.035)	0.485 (+/- 0.048)	6	5^
16x13 cm, Standard Ceph, QuickScan	0.548 (+/- 0.019)	0.473 (+/- 0.042)	3^	2
16x8 cm, Both Arches, Standard*	0.567 (+/- 0.057)	0.495 (+/- 0.058)	7	7
16x8 cm, Both Arches, High Resolution*	0.395 (+/- 0.060)	0.362 (+/- 0.030)	1	1
Reader Reliability (ICC)	0.820	0.884		
Scanner Reliability (ICC)	0.861	0.894		

QuickScan+ (180 degrees, 0.4 mm voxel, 90 kVp, 3 mA, 2.0 s)
QuickScan (180 degrees, 0.3 mm voxel, 120 kVp, 5 mA, 2.0 s)
Standard (360 degrees, 0.3 mm voxel, 120 kVp, 5 mA, 3.7 s)
High Resolution (360 degrees, 0.2 mm voxel, 120 kVp, 5 mA, 7.4 s)
* duplicate scans
^ tied rank order

Table IV. C phantom regression analysis

Percent variation explained by	*Clear separation of 4 lines (R^2)*	*Pattern of 4 lines (R^2)*
Image size	0.073	0.031
Seconds	0.662*	0.548*
Voxel size	0.792*^	0.911*^
kVp	0.442*^	0.663*^
Degrees	0.382	0.361
mA	0.442*	0.633*
Multivariate stepwise analysis		
Voxel size and kVp	0.922	0.944

* significant to P<0.05

^ predictive for resolution

Figure 1. CIC Phantom

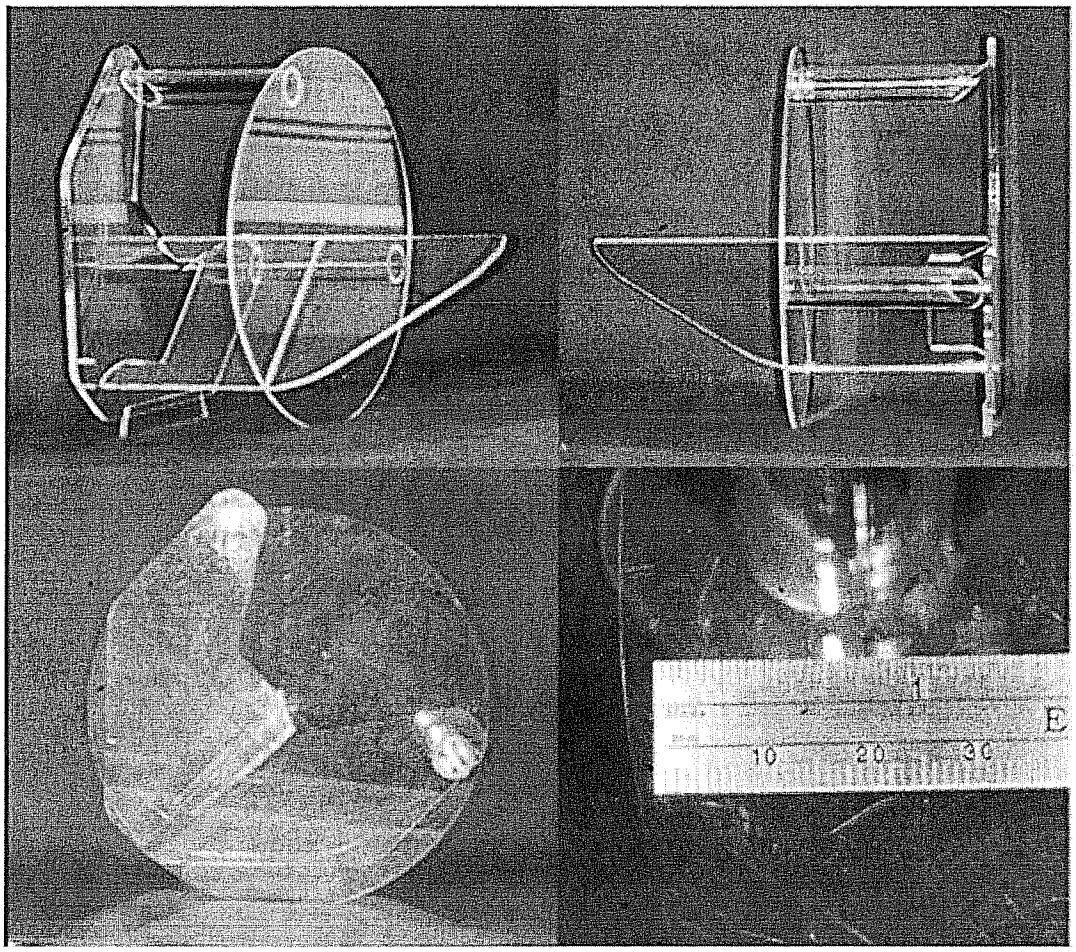


Figure 2. C Phantom

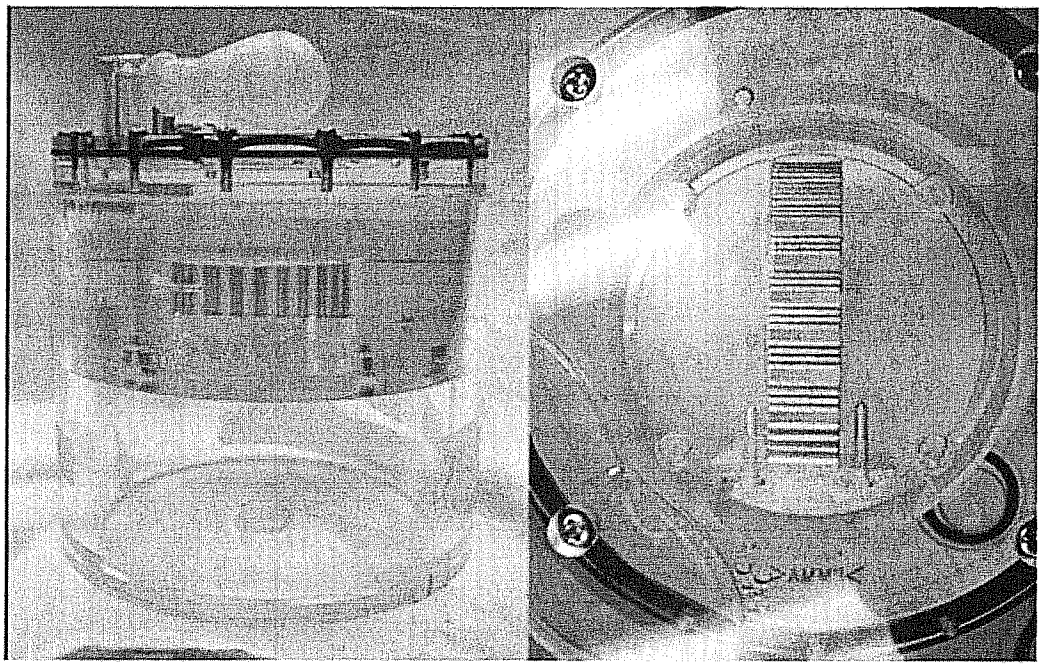


Figure 3. Hitachi resolution test chart

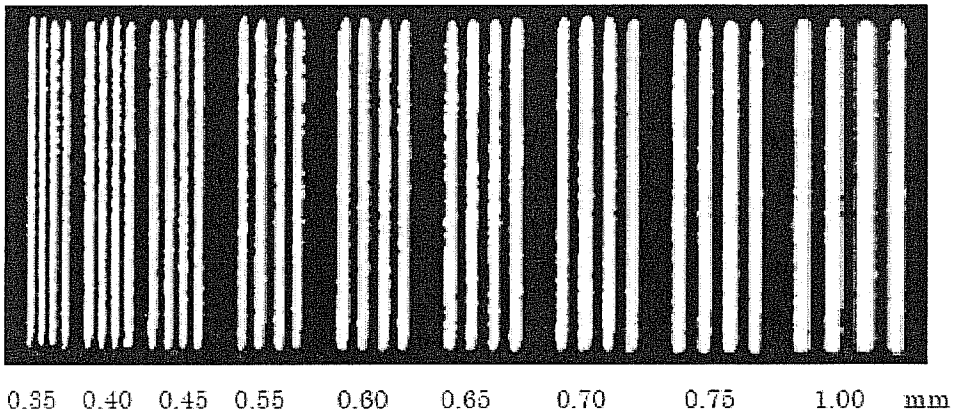


Figure 4. Hitachi Elvis phantom

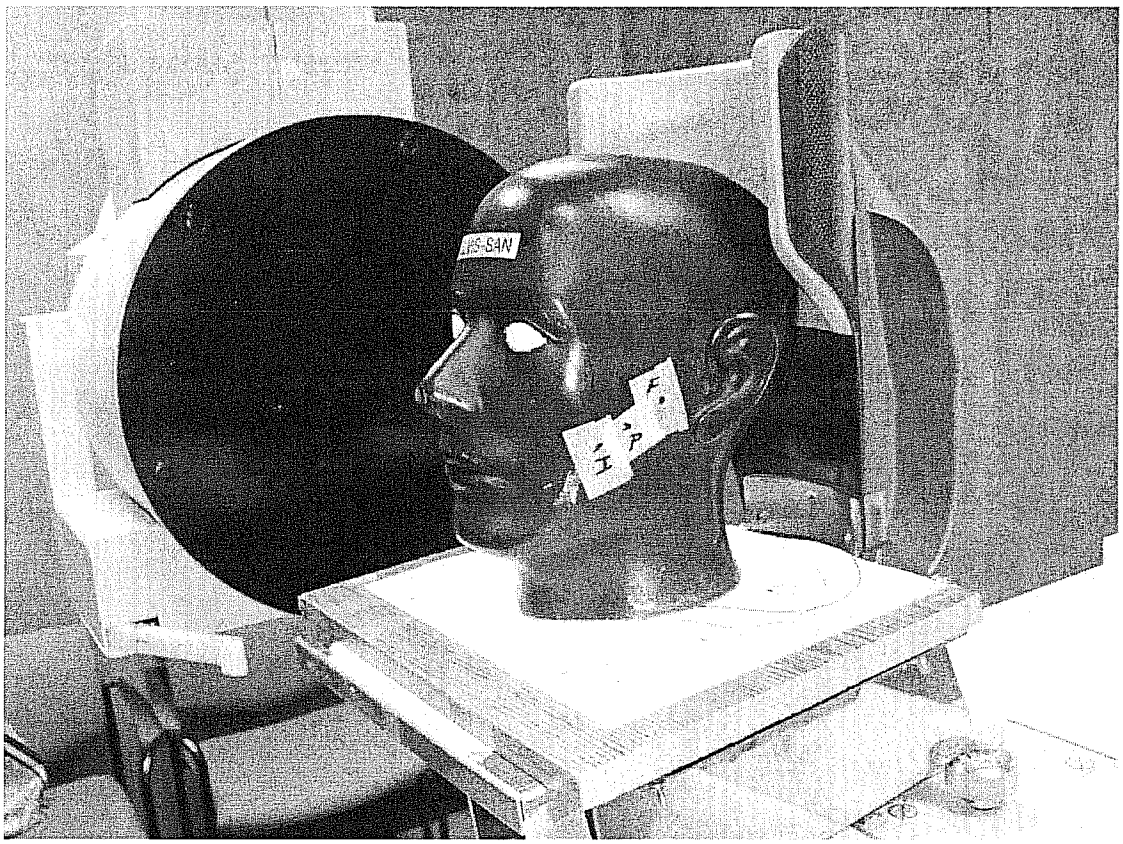
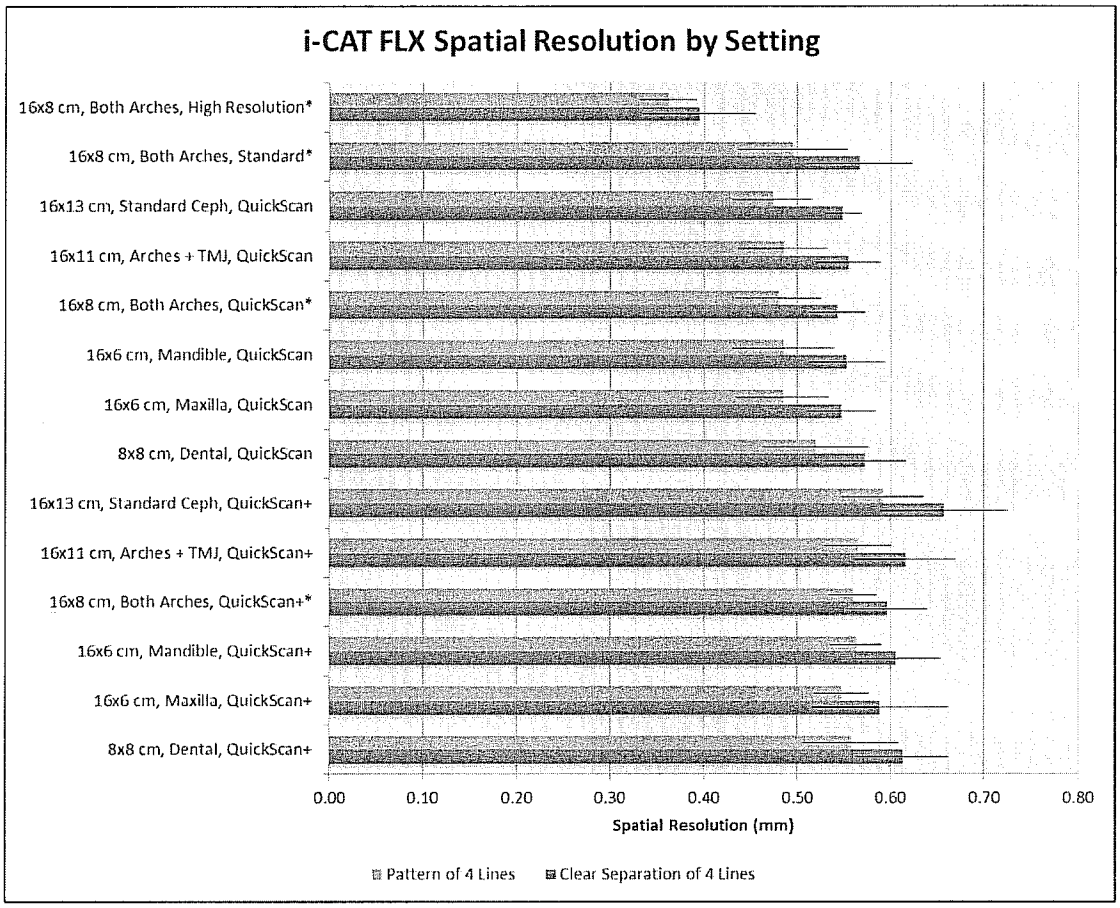


Figure 5. Spatial Resolution of the i-CAT FLX



* duplicate scans

Figure 6. Regression analysis for clear separation

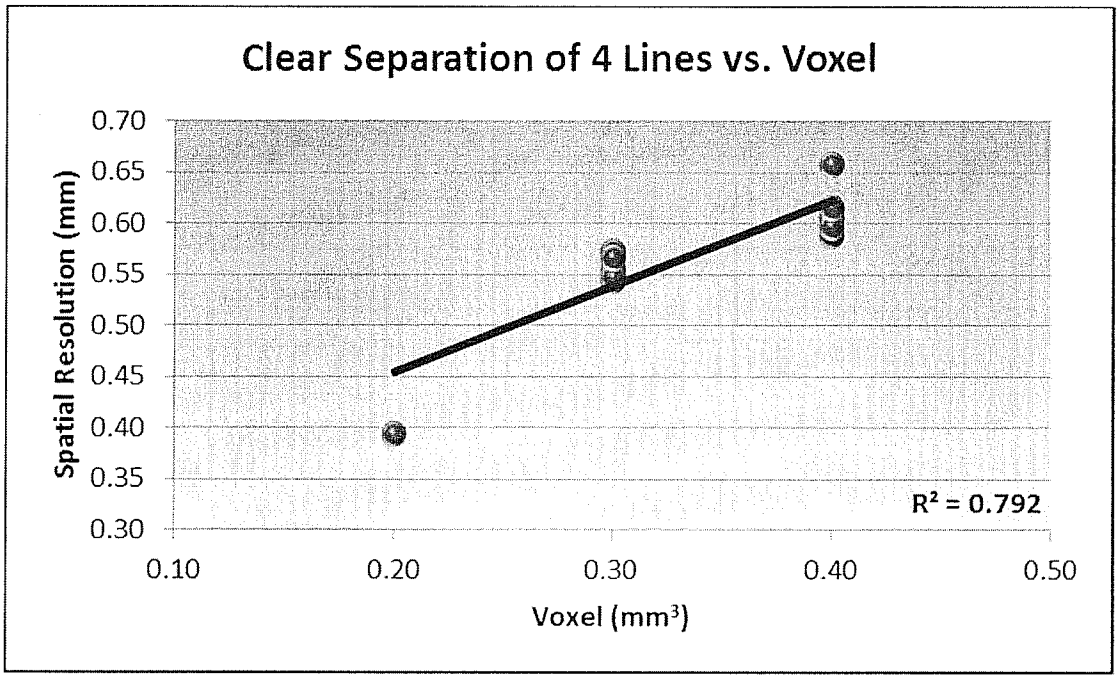
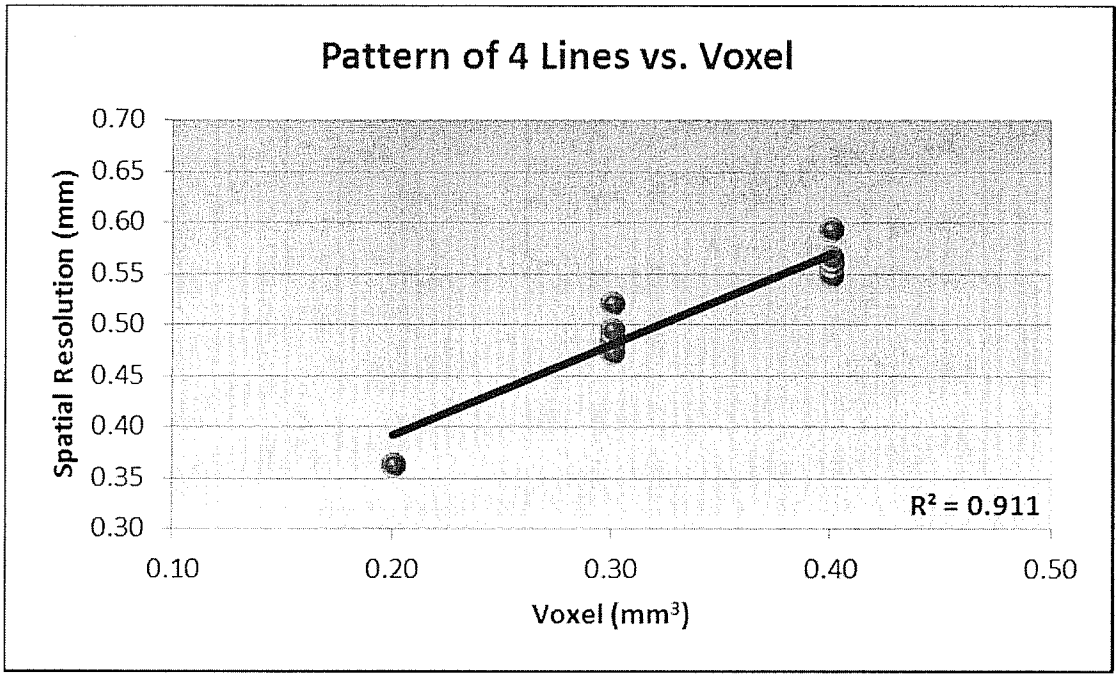


Figure 7. Regression analysis for pattern



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APPENDIX A. IRB approval



TERMINATION – NOT HUMAN SUBJECT RESEARCH

CWRU IRB Protocol Number:	**IRB-2014-839**
Protocol Title:	***Image distortion, spatial resolution, and segmentation capabilities of the i-CAT FLX cone-beam computed tomography machine.***
Responsible Investigator (RI):	**Juan Martin Palomo**
Co-Investigator (CI):	**Alexander Apple, Andres Pinto**
RI Department:	**Orthodontics**
Protocol Expiration Date:	**06/06/2014**

After careful review of the above-referenced protocol submission and our human subject research policies, it has been determined that your protocol – as presented to the IRB and the IRB office – does not fit the definition of human subject research per 45 CFR 46.102. This protocol, therefore, does not require an exemption status, further IRB review, or IRB approval.

The Common Rule or 45 CFR 46 defines a human subject as "a living individual about whom an investigator (whether professional or student) conducting research obtains data through *(1) intervention or interaction with the individual* or *(2) identifiable private information.*"

> **Private information** includes information about behavior that occurs in a context in which an individual can reasonably expect that no observation or recording is taking place, and information that has been provided for specific purposes by an individual and that the individual can reasonably expect will not be made public (for example, a medical record).
>
> Private information must be **individually identifiable** (i.e., the identity of the subject is or may readily be ascertained by the investigator or associated with the information) in order for obtaining the information to constitute research involving human subjects - 45 CFR 46.402(f).

The Common Rule or 45 CFR 46 defines research as a "systematic investigation, including research development, testing and evaluation, designed to develop or contribute to generalizable knowledge."

If the nature of your study changes, contact the IRB office **immediately** and we will be more than happy to assist you. Changes include planning to collect identifiable private information; wanting to expand your subject population, and/or planning to share or present data beyond the Case Western Reserve University campus.

The CWRU IRB would have to determine if an IRB review and approval is necessary prior to any additional research. Also note that if there are changes, you will be asked to complete an iRIS IRB application. Please contact this office at 216-368-6993 with any questions and/or concerns. Thank you for your attention in this matter and good luck with your study.

This is the official notice that *IRB-2014-839– Image distortion, spatial resolution, and segmentation capabilities of the i-CAT FLX cone-beam computed tomography machine,* has been formally closed out. As long as there is no change to the submitted terminated protocol, you may begin your research immediately with no further interaction with the CWRU IRB.

APPENDIX B. Raw Data

Table a. CIC phantom data

scan	height 1	height 2	width 1	width 2	depth 1	depth 2
CICBTHQP	4.9	5.0	6.0	5.2	5.1	5.1
CICBTHQP*	5.0	5.0	6.0	5.1	5.1	5.0
CICBTHQS	5.1	5.0	6.2	5.2	5.2	5.0
CICBTHQS*	5.1	5.2	5.7	5.1	5.2	5.1
CICBTHST	5.1	5.0	5.8	5.0	5.1	4.9
CICBTHST*	5.0	5.0	6.0	4.9	4.9	5.1
CICBTHHR	5.0	5.0	5.8	5.1	5.1	4.9
CICBTHHR*	5.1	5.0	5.8	5.0	4.9	5.0
original 9.2.14						
*repeats 9.3.14						
Average	5.038	5.025	5.913	5.075	5.075	5.013
	5.038	5.025	5.913	5.075	5.075	5.013
SD	0.074	0.071	0.164	0.104	0.116	0.083
	0.074	0.071	0.164	0.104	0.116	0.083

Table b. C phantom data (separation responses)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	C	D	C	D	C	C	C	A	D	D	D	E	D	D	F	D	D	D	D	D	D	D	D	D	D	D	D	D	D	E	D	D	G	D	E	E
2	D	D	D	E	D	D	D	A	D	E	D	E	D	E	F	D	D	D	E	A	D	D	D	E	D	D	D	D	D	A	D	A	D	D	E	E
3	D	D	D	D	D	D	D	A	D	E	E	E	D	E	F	D	D	D	E	B	E	D	D	E	D	D	D	D	D	D	D	A	F	D	E	E
4	D	H	D	F	D	D	D	C	D	E	F	F	D	E	G	D	D	F	F	B	E	D	D	E	D	D	D	C	E	C	D	A	D	D	E	E
5	D	H	D	G	D	D	D	B	D	D	E	E	D	E	F	D	D	E	F	D	H	D	D	E	D	D	D	D	E	D	D	B	D	D	E	E
6	D	E	D	F	D	E	E	D	E	F	G	F	E	F	G	E	F	G	H	D	G	H	F	G	E	F	G	D	E	D	H	D	H	E	H	G
7	C	D	D	D	C	D	D	A	D	E	D	D	C	D	E	C	D	G	D	A	D	H	D	A	C	A	D	A	C	A	D	D	D	D	D	E
8	D	D	D	E	D	D	D	A	D	E	D	E	D	E	F	D	D	D	D	A	E	D	D	A	D	A	D	A	D	A	D	D	F	D	E	E
9	D	D	D	D	D	D	D	A	D	D	D	E	D	D	E	D	D	D	D	A	E	D	D	A	D	A	D	A	D	A	D	D	E	D	E	E
10	D	E	D	F	D	D	D	B	D	E	F	F	D	E	G	D	D	E	F	B	F	D	D	E	D	E	D	E	D	C	D	D	G	D	E	E
11	D	D	D	E	D	C	D	A	D	E	E	D	D	E	F	D	D	D	E	A	E	D	D	E	D	D	D	E	D	C	D	D	G	D	E	E
12	D	D	D	D	C	D	D	A	D	E	E	E	D	E	F	D	D	D	E	A	E	D	D	E	D	D	D	E	D	C	D	D	G	D	E	E
13	D	D	D	E	D	D	D	A	D	D	E	E	D	E	F	D	D	D	E	A	E	D	D	E	D	D	D	E	D	C	D	D	G	D	E	E
14	D	D	D	E	D	E	E	A	D	E	E	E	D	E	F	D	E	D	E	B	E	D	D	E	D	D	D	E	D	C	D	D	G	D	E	E
15	D	D	D	F	D	D	E	B	D	E	E	F	D	E	G	D	E	D	F	B	E	D	D	E	D	D	D	E	D	C	D	D	G	D	E	E
16	D	D	D	D	D	D	A	D	D	D	D	C	C	D	E	D	D	D	D	A	E	D	D	E	D	D	D	E	D	C	D	D	G	D	E	E
17	D	D	D	D	C	D	D	A	D	E	E	E	D	E	G	E	D	E	E	B	E	D	D	E	D	D	D	E	D	C	D	D	G	D	E	E
18	D	D	D	E	D	D	D	A	D	E	E	E	D	E	F	D	D	D	E	A	E	D	D	E	D	D	D	E	D	C	D	D	G	D	E	E
19	D	E	D	E	D	D	D	C	C	E	E	E	E	E	F	E	E	E	F	B	F	E	E	F	D	E	E	C	D	C	F	D	G	D	F	G
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22	D	D	D	E	D	D	D	A	D	E	E	D	D	E	F	D	D	D	E	A	E	D	D	E	D	E	D	A	D	A	D	D	F	D	D	D
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Table c. C phantom data (separation analysis)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
1	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.55	0.55	0.55	0.60	0.55	0.60	0.65	0.55	0.55	0.55	0.55	0.35	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.35	0.55	0.55	0.55	0.70	0.55	0.60	A 0.35
2	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.60	0.60	0.60	0.55	0.60	0.65	0.55	0.55	0.55	0.55	0.40	0.60	0.60	0.55	0.60	0.55	0.55	0.60	0.40	0.55	0.40	0.55	0.55	0.55	0.65	0.55	0.60	B 0.40
3	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.55	0.60	0.60	0.60	0.60	0.60	0.65	0.55	0.55	0.55	0.55	0.40	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.35	0.55	0.55	0.60	0.55	0.60	0.60	C 0.45
4	0.55	0.75	0.55	0.65	0.55	0.55	0.60	0.45	0.55	0.60	0.65	0.65	0.55	0.60	0.70	0.55	0.55	0.65	0.65	0.40	0.60	0.55	0.55	0.65	0.55	0.55	0.55	0.45	0.60	0.45	0.55	0.55	0.75	0.55	0.70	0.70	D 0.55
5	0.55	0.75	0.55	0.70	0.55	0.55	0.55	0.40	0.55	0.55	0.60	0.60	0.55	0.60	0.65	0.55	0.55	0.60	0.65	0.55	0.75	0.55	0.55	0.70	0.55	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.55	0.75	0.55	0.70	E 0.60
6	0.55	0.60	0.55	0.65	0.55	0.60	0.60	0.55	0.60	0.65	0.70	0.65	0.60	0.65	0.70	0.60	0.65	0.70	0.75	0.55	0.70	0.75	0.55	0.70	0.60	0.65	0.70	0.55	0.60	0.55	0.75	0.55	0.75	0.60	0.75	0.70	F 0.65
7	0.45	0.55	0.55	0.55	0.45	0.45	0.55	0.35	0.55	0.55	0.55	0.55	0.45	0.55	0.60	0.45	0.55	0.55	0.55	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.45	0.35	0.55	0.55	0.55	0.55	0.55	0.60	G 0.70
8	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.60	0.55	0.60	0.55	0.60	0.65	0.55	0.55	0.55	0.55	0.35	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.35	0.55	0.55	0.55	0.65	0.55	0.60	H 0.75
9	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.55	0.55	0.55	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.55	0.35	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.35	0.55	0.55	0.55	0.60	0.55	0.55	I 1.00
10	0.55	0.60	0.55	0.65	0.55	0.55	0.55	0.40	0.55	0.60	0.65	0.65	0.55	0.60	0.70	0.55	0.55	0.60	0.65	0.40	0.65	0.55	0.60	0.65	0.55	0.60	0.60	0.45	0.60	0.40	0.55	0.55	0.55	0.70	0.55	0.65	
11	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.60	0.60	0.55	0.55	0.60	0.60	0.55	0.60	0.55	0.60	0.35	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.40	0.55	0.55	0.55	0.65	0.55	0.60	
12	0.55	0.55	0.55	0.55	0.45	0.55	0.55	0.35	0.55	0.60	0.60	0.60	0.55	0.60	0.65	0.55	0.55	0.55	0.60	0.35	0.60	0.55	0.55	0.60	0.55	0.45	0.55	0.35	0.55	0.35	0.55	0.55	0.55	0.60	0.55	0.60	
13	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.60	0.60	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.60	0.35	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.40	0.55	0.55	0.55	0.65	0.55	0.60	
14	0.55	0.55	0.55	0.60	0.55	0.60	0.60	0.35	0.55	0.60	0.60	0.60	0.55	0.60	0.60	0.55	0.55	0.60	0.60	0.40	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.40	0.55	0.40	0.55	0.55	0.55	0.65	0.55	0.65	
15	0.55	0.55	0.55	0.65	0.55	0.55	0.55	0.40	0.55	0.65	0.65	0.65	0.55	0.65	0.70	0.55	0.60	0.60	0.65	0.40	0.60	0.60	0.60	0.60	0.55	0.60	0.60	0.40	0.55	0.40	0.65	0.55	0.55	0.70	0.55	0.65	
16	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.55	0.55	0.55	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.55	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.55	0.40	0.55	0.55	0.55	0.55	0.55	0.60	
17	0.55	0.55	0.55	0.55	0.45	0.55	0.55	0.35	0.55	0.60	0.60	0.60	0.55	0.60	0.70	0.60	0.55	0.60	0.60	0.40	0.65	0.55	0.55	0.60	0.55	0.55	0.60	0.40	0.55	0.40	0.55	0.55	0.55	0.70	0.55	0.65	
18	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.55	0.55	0.60	0.55	0.60	0.65	0.55	0.55	0.60	0.60	0.40	0.65	0.55	0.55	0.60	0.55	0.55	0.55	0.40	0.55	0.40	0.55	0.55	0.55	0.70	0.55	0.70	
19	0.55	0.60	0.55	0.60	0.55	0.55	0.55	0.45	0.55	0.55	0.60	0.60	0.55	0.60	0.65	0.55	0.55	0.55	0.60	0.35	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.40	0.55	0.40	0.55	0.55	0.55	0.70	0.55	0.70	
20	0.55	0.70	0.65	0.65	0.55	0.55	0.60	0.45	0.65	0.75	0.75	0.65	0.60	0.75	0.70	0.60	0.55	0.60	0.70	0.45	0.65	0.60	0.65	0.65	0.55	0.65	0.60	0.45	0.60	0.45	0.60	0.55	0.70	0.55	0.65	0.70	
21	0.55	0.55	0.55	0.55	0.55	0.55	0.60	0.40	0.55	0.60	0.60	0.60	0.55	0.60	0.65	0.60	0.60	0.60	0.65	0.40	0.60	0.60	0.55	0.60	0.60	0.55	0.60	0.40	0.55	0.40	0.55	0.55	0.65	0.55	0.60	0.60	
22	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.60	0.35	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.40	0.55	0.40	0.55	0.55	0.55	0.55	0.55	0.55	
23	0.55	0.55	0.55	0.60	0.60	0.60	0.60	0.40	0.60	0.60	0.65	0.65	0.60	0.60	0.60	0.55	0.55	0.60	0.60	0.40	0.60	0.60	0.60	0.60	0.55	0.60	0.60	0.40	0.55	0.40	0.55	0.55	0.60	0.55	0.55	0.55	
24	0.55	0.55	0.45	0.55	0.45	0.45	0.55	0.35	0.55	0.60	0.60	0.60	0.55	0.60	0.65	0.55	0.55	0.60	0.60	0.40	0.60	0.55	0.55	0.60	0.55	0.60	0.60	0.40	0.55	0.40	0.55	0.55	0.55	0.60	0.55	0.70	
25	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.55	0.55	0.60	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.60	0.40	0.60	0.60	0.60	0.60	0.55	0.60	0.60	0.40	0.55	0.40	0.60	0.55	0.60	0.55	0.60	0.60	
26	0.55	0.60	0.55	0.65	0.55	0.60	0.55	0.40	0.60	0.65	0.65	0.60	0.60	0.65	0.75	0.60	0.60	1.00	0.75	0.55	0.70	0.70	0.70	0.70	0.60	0.70	0.65	0.60	0.60	0.55	1.00	0.60	1.00	0.60	0.70	0.75	
27	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.55	0.60	0.60	0.55	0.55	0.65	0.55	0.55	0.60	0.60	0.40	0.60	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.35	0.55	0.55	0.65	0.55	0.60	0.65	
28	0.55	0.55	0.55	0.55	0.45	0.55	0.45	0.35	0.55	0.55	0.55	0.55	0.45	0.55	0.60	0.45	0.45	0.55	0.60	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.55	0.35	0.55	0.55	0.55	0.55	0.55	0.55	
29	0.55	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.55	0.35	0.55	0.55	0.55	0.55	0.55	0.55	
30	0.55	0.60	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.60	0.60	0.60	0.55	0.60	0.75	0.55	0.55	0.70	0.65	0.40	0.65	0.60	0.55	0.65	0.55	0.60	0.60	0.40	0.60	0.40	0.60	0.55	0.55	0.70	0.55	0.70	
SLIDE	32	3	4	19	16	34	9	28	22	7	23	33	6	25	13	30	24	21	29	18	5	20	35	15	26	17	2	10	12	36	27	8	31	14	11	1	
AVG	0.54	0.58	0.54	0.59	0.53	0.54	0.55	0.38	0.55	0.59	0.60	0.59	0.55	0.60	0.65	0.55	0.56	0.60	0.61	0.40	0.61	0.57	0.57	0.61	0.55	0.57	0.57	0.40	0.56	0.40	0.58	0.55	0.67	0.55	0.62	0.64	
	0.54	0.58	0.54	0.59	0.53	0.54	0.55	0.38	0.55	0.59	0.60	0.59	0.55	0.60	0.65	0.55	0.56	0.60	0.61	0.40	0.61	0.57	0.57	0.61	0.55	0.57	0.57	0.40	0.56	0.40	0.58	0.55	0.67	0.55	0.62	0.64	
SD	0.03	0.06	0.04	0.04	0.04	0.05	0.05	0.06	0.04	0.04	0.05	0.04	0.04	0.04	0.05	0.04	0.04	0.09	0.05	0.06	0.05	0.04	0.04	0.04	0.02	0.04	0.04	0.07	0.03	0.06	0.09	0.01	0.09	0.01	0.05	0.05	
	0.03	0.06	0.04	0.04	0.04	0.05	0.05	0.06	0.04	0.04	0.05	0.04	0.04	0.04	0.05	0.04	0.04	0.09	0.05	0.06	0.05	0.05	0.04	0.04	0.02	0.04	0.04	0.07	0.03	0.06	0.09	0.01	0.09	0.01	0.05	0.05	

Table d. C phantom data (pattern responses)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	C	D	C	C	C	C	C	C	C	D	D	D	C	C	D	C	C	C	D	D	C	C	C	C	C	C	C	C	D	D
2	C	D	D	D	C	C	D	A	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
3	C	D	C	D	C	C	C	A	C	D	D	D	C	D	E	C	D	D	D	A	D	C	D	D	C	D	D	D	D	D
4	C	D	D	E	D	D	D	A	D	D	E	E	D	D	F	D	D	D	E	A	D	D	D	E	D	D	D	D	E	E
5	C	D	C	D	C	C	C	A	C	D	D	D	C	D	D	C	C	C	D	A	D	C	C	D	C	C	C	C	D	D
6	C	D	D	E	D	C	D	C	D	E	E	E	D	D	F	D	C	C	D	A	D	C	C	D	C	C	C	C	F	E
7	D	D	D	E	D	C	D	C	D	E	E	E	D	D	F	D	D	D	E	A	E	D	E	E	D	D	D	B	E	E
8	C	D	C	D	C	C	C	A	C	D	D	D	C	D	D	C	C	C	D	A	D	D	C	D	C	C	C	D	D	D
9	C	D	C	D	C	C	C	A	C	D	D	D	C	D	D	C	C	C	D	A	D	D	C	D	C	C	C	D	D	D
10	C	D	D	D	C	C	C	A	C	D	D	D	C	D	D	C	C	C	D	A	D	D	C	D	C	C	C	D	D	D
11	C	D	C	D	C	C	C	A	C	D	D	D	C	D	D	C	C	C	D	A	D	D	C	D	C	C	C	D	D	D
12	C	D	C	D	C	C	C	A	C	D	D	D	C	D	D	C	C	C	D	A	D	D	C	D	C	C	C	D	D	D
13	C	D	C	C	C	C	C	A	C	D	D	D	C	D	D	C	C	C	D	A	D	D	C	D	C	C	C	D	D	D
14	C	D	C	D	C	C	D	A	C	D	D	D	C	D	F	C	C	C	D	A	D	D	C	D	C	C	C	D	D	D
15	D	D	D	F	D	C	D	C	D	D	F	F	F	F	G	D	E	E	F	B	F	F	F	E	D	E	E	E	E	E
16	C	D	C	D	C	C	C	A	C	D	D	D	D	D	D	C	C	C	D	A	D	D	D	D	C	C	C	D	D	D
17	C	D	C	D	C	C	C	A	C	D	D	D	C	D	E	D	C	C	D	A	D	D	D	D	C	D	C	C	C	C
18	C	D	D	D	C	C	C	A	C	D	D	D	C	D	E	C	C	D	D	A	D	D	D	D	C	D	C	C	C	C
19	D	D	D	D	C	C	D	A	B	D	D	D	C	D	E	D	C	D	D	A	D	D	D	D	C	D	C	C	C	C
20	D	D	D	E	D	D	E	C	D	F	F	E	D	E	E	D	D	E	F	B	E	E	D	E	D	D	D	B	C	C
21	C	D	C	E	C	C	D	A	D	D	D	D	D	D	E	D	C	D	D	A	D	D	D	D	C	D	D	D	C	C
22	C	D	C	C	C	C	C	A	C	D	D	D	D	D	E	D	C	D	D	A	D	D	D	D	C	D	D	D	C	C
23	C	D	C	D	C	C	C	A	C	D	D	D	D	D	E	D	C	D	D	A	D	D	D	D	C	D	D	D	C	C
24	C	C	C	C	C	C	C	A	C	D	D	D	C	D	D	C	C	D	D	A	D	D	C	D	C	D	D	D	C	C
25	C	D	C	D	C	C	D	A	C	D	D	D	C	D	E	C	C	D	D	A	D	D	C	D	C	D	D	D	C	C
26	C	D	C	E	C	D	C	A	D	E	E	D	D	E	F	C	C	D	D	B	E	D	D	D	C	D	D	B	C	C
27	C	D	C	D	C	C	C	A	C	D	D	D	C	D	E	C	C	D	D	A	D	D	D	D	C	D	C	A	C	C
28	C	D	C	D	C	C	C	A	C	D	D	D	C	D	D	C	C	D	D	A	D	D	D	D	C	D	C	A	C	C
29	C	C	C	C	C	C	B	A	C	D	D	D	C	D	D	C	B	C	D	A	D	C	C	D	C	D	C	A	C	C
30	D	D	D	D	C	D	C	A	D	D	D	D	C	D	G	D	D	E	E	A	D	D	E	E	D	D	D	A	D	D

Table e. C phantom data (pattern analysis)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
1	0.45	0.55	0.45	0.45	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.60	0.45	0.45	0.55	0.55	0.35	0.55	0.45	0.45	0.55	0.45	0.45	0.55	0.35	0.45	0.35	0.45	0.55	0.65	0.45	0.55	0.55	A 0.35
2	0.45	0.55	0.55	0.55	0.45	0.45	0.55	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.60	0.55	0.45	0.55	0.55	0.35	0.60	0.55	0.55	0.55	0.55	0.55	0.45	0.35	0.55	0.35	0.55	0.55	0.60	0.55	0.55	0.60	B 0.40
3	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.60	0.45	0.45	0.55	0.55	0.35	0.55	0.45	0.55	0.55	0.55	0.45	0.45	0.35	0.45	0.35	0.55	0.45	0.55	0.55	0.55	0.55	C 0.45
4	0.45	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.55	0.60	0.60	0.55	0.55	0.65	0.55	0.55	0.55	0.60	0.35	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.40	0.55	0.40	0.55	0.55	0.65	0.55	0.60	0.60	D 0.55
5	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.45	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.35	0.45	0.45	0.60	0.45	0.55	0.55	E 0.60
6	0.45	0.55	0.55	0.60	0.55	0.55	0.55	0.45	0.55	0.55	0.60	0.60	0.55	0.60	0.65	0.55	0.55	0.60	0.65	0.55	0.60	0.65	0.55	0.60	0.55	0.60	0.60	0.45	0.45	0.40	0.60	0.55	0.65	0.55	0.65	0.60	F 0.65
7	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.40	0.55	0.60	0.60	0.60	0.55	0.60	0.65	0.55	0.55	0.60	0.60	0.35	0.60	0.55	0.60	0.60	0.55	0.55	0.55	0.40	0.55	0.35	0.55	0.55	0.60	0.55	0.60	0.60	G 0.70
8	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.35	0.45	0.35	0.45	0.45	0.55	0.45	0.55	0.55	H 0.75
9	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.35	0.55	0.35	0.45	0.45	0.60	0.45	0.55	0.55	I 1.00
10	0.45	0.55	0.55	0.55	0.55	0.45	0.55	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.45	0.55	0.55	0.45	0.45	0.45	0.35	0.45	0.35	0.45	0.45	0.55	0.45	0.55	0.55	
11	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.35	0.45	0.45	0.60	0.45	0.55	0.55	
12	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.35	0.45	0.45	0.60	0.45	0.55	0.55	
13	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.35	0.45	0.45	0.60	0.45	0.55	0.55	
14	0.45	0.55	0.45	0.55	0.45	0.45	0.55	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.55	0.45	0.55	0.45	0.45	0.55	0.35	0.45	0.35	0.45	0.45	0.55	0.45	0.55	0.55	
15	0.55	0.55	0.55	0.65	0.55	0.55	0.60	0.45	0.55	0.65	0.65	0.60	0.65	0.65	0.70	0.55	0.60	0.60	0.65	0.40	0.65	0.65	0.65	0.60	0.60	0.60	0.60	0.40	0.55	0.40	0.65	0.55	0.70	0.55	0.65	0.70	
16	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.55	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.35	0.45	0.45	0.60	0.45	0.55	0.55	
17	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.60	0.55	0.45	0.55	0.55	0.35	0.55	0.55	0.55	0.55	0.45	0.55	0.55	0.35	0.55	0.35	0.55	0.55	0.65	0.55	0.60	0.60	
18	0.45	0.55	0.55	0.55	0.45	0.45	0.55	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.60	0.45	0.45	0.55	0.55	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.55	0.35	0.55	0.55	0.60	0.55	0.55	0.55	
19	0.55	0.55	0.55	0.55	0.45	0.45	0.55	0.40	0.55	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.55	0.55	0.55	0.45	0.55	0.55	0.35	0.55	0.45	0.55	0.45	0.55	0.45	0.55	0.55	
20	0.55	0.55	0.55	0.60	0.55	0.55	0.60	0.45	0.55	0.65	0.60	0.60	0.55	0.60	0.60	0.55	0.55	0.60	0.65	0.40	0.60	0.60	0.55	0.60	0.55	0.60	0.55	0.40	0.55	0.40	0.55	0.55	0.65	0.55	0.65	0.65	
21	0.45	0.55	0.45	0.60	0.45	0.45	0.45	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.55	0.35	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.45	0.35	0.55	0.55	0.60	0.45	0.55	0.55	
22	0.45	0.55	0.45	0.45	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.45	0.35	0.45	0.35	0.45	0.45	0.60	0.45	0.55	0.55	
23	0.45	0.55	0.45	0.55	0.55	0.55	0.55	0.35	0.55	0.55	0.60	0.60	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.35	0.55	0.55	0.55	0.55	0.55	0.55	0.45	0.35	0.45	0.35	0.45	0.45	0.55	0.45	0.45	0.45	
24	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.45	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.35	0.45	0.45	0.55	0.45	0.55	0.45	
25	0.45	0.55	0.45	0.55	0.45	0.45	0.55	0.35	0.45	0.55	0.55	0.55	0.55	0.55	0.60	0.55	0.45	0.55	0.55	0.35	0.55	0.55	0.45	0.55	0.45	0.55	0.55	0.35	0.55	0.35	0.55	0.55	0.60	0.45	0.55	0.55	
26	0.45	0.55	0.45	0.60	0.45	0.55	0.45	0.35	0.55	0.60	0.60	0.55	0.55	0.60	0.65	0.45	0.45	0.55	0.55	0.40	0.60	0.55	0.55	0.55	0.45	0.55	0.55	0.40	0.45	0.45	0.55	0.55	0.60	0.45	0.60	0.65	
27	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.60	0.45	0.45	0.55	0.55	0.35	0.55	0.45	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.35	0.45	0.45	0.60	0.45	0.55	0.55	
28	0.45	0.55	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.45	0.55	0.55	0.35	0.55	0.45	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.35	0.45	0.45	0.55	0.45	0.55	0.55	
29	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.35	0.45	0.55	0.55	0.55	0.45	0.55	0.55	0.45	0.40	0.45	0.55	0.35	0.55	0.45	0.45	0.55	0.45	0.45	0.45	0.35	0.45	0.35	0.45	0.45	0.55	0.45	0.55	0.55	
30	0.55	0.55	0.55	0.55	0.45	0.55	0.45	0.35	0.55	0.55	0.55	0.60	0.55	0.45	0.70	0.55	0.55	0.60	0.60	0.35	0.55	0.55	0.55	0.60	0.55	0.55	0.55	0.35	0.55	0.40	0.55	0.55	0.65	0.55	0.60	0.60	
SLIDE	32	3	4	19	16	34	9	28	22	7	23	33	6	25	13	30	24	21	29	18	5	20	35	15	26	17	2	10	12	36	27	8	31	14	11	1	
AVG	0.47	0.54	0.48	0.55	0.47	0.48	0.49	0.36	0.49	0.56	0.57	0.56	0.49	0.56	0.59	0.49	0.48	0.55	0.57	0.36	0.56	0.53	0.50	0.56	0.48	0.49	0.51	0.36	0.48	0.36	0.50	0.49	0.60	0.48	0.57	0.57	
	0.47	0.54	0.48	0.55	0.47	0.48	0.49	0.36	0.49	0.56	0.57	0.56	0.49	0.56	0.59	0.49	0.48	0.55	0.57	0.36	0.56	0.53	0.50	0.56	0.48	0.49	0.51	0.36	0.48	0.36	0.50	0.49	0.60	0.48	0.57	0.57	
SD	0.04	0.03	0.05	0.05	0.04	0.04	0.06	0.03	0.05	0.03	0.03	0.02	0.06	0.03	0.05	0.05	0.05	0.03	0.03	0.04	0.03	0.06	0.02	0.05	0.06	0.06	0.06	0.03	0.05	0.03	0.06	0.05	0.04	0.05	0.04	0.05	
	0.04	0.03	0.05	0.05	0.04	0.04	0.06	0.03	0.05	0.03	0.03	0.02	0.06	0.03	0.05	0.05	0.05	0.03	0.03	0.04	0.03	0.06	0.02	0.05	0.06	0.06	0.06	0.03	0.05	0.03	0.06	0.05	0.04	0.05	0.04	0.05	

Table f. C phantom data (Key)

SLIDE	NAME	Distinction Average	Distinction SD	Pattern Average	Pattern SD	Combined Distinction Average	Combined Pattern Average
1	CPHDENQP	0.635	0.054	0.565	0.054	0.613	0.558
2	CPHDENQS	0.573	0.037	0.507	0.055	0.573	0.520
3	CPHMAXQP	0.577	0.057	0.543	0.025	0.588	0.548
4	CPHMAXQS	0.543	0.037	0.483	0.048	0.548	0.484
5	CPHMANQP	0.612	0.047	0.562	0.025	0.606	0.563
6	CPHMANQS	0.552	0.043	0.493	0.057	0.553	0.481
7	CPHBTHQP	0.588	0.043	0.560	0.028	0.597	0.560
8	CPHBTHQS	0.552	0.009	0.490	0.050	0.543	0.480
9	CPHBTHST	0.545	0.055	0.492	0.057	0.567	0.495
10	CPHBTHHR	0.400	0.067	0.362	0.025	0.395	0.362
11	CPHTMUQP	0.618	0.055	0.565	0.040	0.616	0.565
12	CPHTMUQS	0.558	0.030	0.483	0.048	0.555	0.485
13	CPHCEPQP	0.647	0.049	0.588	0.047	0.658	0.593
14	CPHCEPQS	0.553	0.013	0.480	0.047	0.548	0.473
15	CPHDUPQP	0.612	0.041	0.562	0.022		
16	CPHDUPQS	0.528	0.045	0.473	0.043		
17	CPHDUPST	0.568	0.044	0.492	0.057		
18	CPHDUPHR	0.397	0.059	0.362	0.039		
19	CPHDENQP	0.592	0.044	0.550	0.047		
20	CPHDENQS	0.572	0.052	0.533	0.058		
21	CPHMAXQP	0.600	0.089	0.552	0.033		
22	CPHMAXQS	0.552	0.036	0.485	0.051		
23	CPHMANQP	0.600	0.047	0.565	0.030		
24	CPHMANQS	0.555	0.038	0.477	0.050		
25	CPHBTHQP	0.595	0.042	0.557	0.031		
26	CPHBTHQS	0.550	0.023	0.480	0.047		
27	CPHBTHST	0.583	0.090	0.498	0.059		
28	CPHBTHHR	0.383	0.056	0.362	0.031		
29	CPHTMUQP	0.613	0.054	0.565	0.033		
30	CPHTMUQS	0.552	0.040	0.487	0.049		
31	CPHCEPQP	0.668	0.086	0.597	0.041		
32	CPHCEPQS	0.543	0.025	0.467	0.038		
33	CPHDUPQP	0.593	0.041	0.562	0.022		
34	CPHDUPQS	0.542	0.046	0.477	0.045		
35	CPHDUPST	0.570	0.039	0.498	0.059		
36	CPHDUPHR	0.400	0.060	0.362	0.025		

Combined Distinction SD	Combined Pattern SD
0.049	0.051
0.044	0.057
0.073	0.029
0.036	0.050
0.047	0.027
0.040	0.054
0.042	0.026
0.031	0.046
0.057	0.058
0.060	0.030
0.054	0.036
0.035	0.048
0.067	0.044
0.019	0.042

Table g. C phantom data (separation sort)

SLIDE	NAME	Distinction Average	Distinction SD	Pattern Average	Pattern SD	Combined Distinction Average	Combined Pattern Average
28	CPHBTHHR	0.383	0.056	0.362	0.031	0.395	0.362
18	CPHDUPHR	0.397	0.059	0.362	0.039	0.543	0.480
10	CPHBTHHR	0.400	0.067	0.362	0.025	0.548	0.484
36	CPHDUPHR	0.400	0.060	0.362	0.025	0.548	0.473
16	CPHDUPQS	0.528	0.045	0.473	0.043	0.553	0.485
34	CPHDUPQS	0.542	0.046	0.477	0.045	0.555	0.485
4	CPHMAXQS	0.543	0.037	0.483	0.048	0.567	0.495
32	CPHCEPQS	0.543	0.025	0.467	0.038	0.573	0.520
9	CPHBTHST	0.545	0.055	0.492	0.057	0.588	0.548
26	CPHBTHQS	0.550	0.023	0.480	0.047	0.597	0.560
6	CPHMANQS	0.552	0.043	0.493	0.057	0.606	0.563
30	CPHTMUQS	0.552	0.040	0.487	0.049	0.613	0.558
22	CPHMAXQS	0.552	0.036	0.485	0.051	0.616	0.565
8	CPHBTHQS	0.552	0.009	0.490	0.050	0.658	0.593
14	CPHCEPQS	0.553	0.013	0.480	0.047		
24	CPHMANQS	0.555	0.038	0.477	0.050		
12	CPHTMUQS	0.558	0.030	0.483	0.048		
17	CPHDUPST	0.568	0.044	0.492	0.057		
35	CPHDUPST	0.570	0.039	0.498	0.059		
20	CPHDENQS	0.572	0.052	0.533	0.058		
2	CPHDENQS	0.573	0.037	0.507	0.055		
3	CPHMAXQP	0.577	0.057	0.543	0.025		
27	CPHBTHST	0.583	0.090	0.498	0.059		
7	CPHBTHQP	0.588	0.043	0.560	0.028		
19	CPHDENQP	0.592	0.044	0.550	0.047		
33	CPHDUPQP	0.593	0.041	0.562	0.022		
25	CPHBTHQP	0.595	0.042	0.557	0.031		
21	CPHMAXQP	0.600	0.089	0.552	0.033		
23	CPHMANQP	0.600	0.047	0.565	0.030		
5	CPHMANQP	0.612	0.047	0.562	0.025		
15	CPHDUPQP	0.612	0.041	0.562	0.022		
29	CPHTMUQP	0.613	0.054	0.565	0.033		
11	CPHTMUQP	0.618	0.055	0.565	0.040		
1	CPHDENQP	0.635	0.054	0.565	0.054		
13	CPHCEPQP	0.647	0.049	0.588	0.047		
31	CPHCEPQP	0.668	0.086	0.597	0.041		

Table h. C phantom data (pattern sort)

SLIDE	NAME	Distinction Average	Distinction SD	Pattern Average	Pattern SD	Combined Distinction Average	Combined Pattern Average
28	CPHBTHHR	0.383	0.056	0.362	0.031	0.395	0.362
10	CPHBTHHR	0.400	0.067	0.362	0.025	0.548	0.473
18	CPHDUPHR	0.397	0.059	0.362	0.039	0.543	0.480
36	CPHDUPHR	0.400	0.060	0.362	0.025	0.548	0.484
32	CPHCEPQS	0.543	0.025	0.467	0.038	0.553	0.485
16	CPHDUPQS	0.528	0.045	0.473	0.043	0.555	0.485
34	CPHDUPQS	0.542	0.046	0.477	0.045	0.567	0.495
24	CPHMANQS	0.555	0.038	0.477	0.050	0.573	0.520
14	CPHCEPQS	0.553	0.013	0.480	0.047	0.588	0.548
26	CPHBTHQS	0.550	0.023	0.480	0.047	0.613	0.558
4	CPHMAXQS	0.543	0.037	0.483	0.048	0.597	0.560
12	CPHTMJQS	0.558	0.030	0.483	0.048	0.606	0.563
22	CPHMAXQS	0.552	0.036	0.485	0.051	0.616	0.565
30	CPHTMJQS	0.552	0.040	0.487	0.049	0.658	0.593
8	CPHBTHQS	0.552	0.009	0.490	0.050		
9	CPHBTHST	0.545	0.055	0.492	0.057		
17	CPHDUPST	0.568	0.044	0.492	0.057		
6	CPHMANQS	0.552	0.043	0.493	0.057		
27	CPHBTHST	0.583	0.090	0.498	0.059		
35	CPHDUPST	0.570	0.039	0.498	0.059		
2	CPHDENQS	0.573	0.037	0.507	0.055		
20	CPHDENQS	0.572	0.052	0.533	0.058		
3	CPHMAXQP	0.577	0.057	0.543	0.025		
19	CPHDENQP	0.592	0.044	0.550	0.047		
21	CPHMAXQP	0.600	0.089	0.552	0.033		
25	CPHBTHQP	0.595	0.042	0.557	0.031		
7	CPHBTHQP	0.588	0.043	0.560	0.028		
5	CPHMANQP	0.612	0.047	0.562	0.025		
15	CPHDUPQP	0.612	0.041	0.562	0.022		
33	CPHDUPQP	0.593	0.041	0.562	0.022		
1	CPHDENQP	0.635	0.054	0.565	0.054		
11	CPHTMJQP	0.618	0.055	0.565	0.040		
23	CPHMANQP	0.600	0.047	0.565	0.030		
29	CPHTMJQP	0.613	0.054	0.565	0.033		
13	CPHCEPQP	0.647	0.049	0.588	0.047		
31	CPHCEPQP	0.668	0.086	0.597	0.041		