RESEARCH

The influence of exposure parameters on jawbone model accuracy using cone beam CT and multislice CT

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Objective: The main purpose of this study was to investigate the influence of exposure parameters on jawbone model accuracy when using cone beam CT (CBCT) and multislice CT (MSCT).

Methods: A lower and an upper edentulous human cadaver jaw were scanned using micro-CT (Skyscan 1173 high energy spiral scan micro-CT; Skyscan NV, Kontich, Belgium) at 35 µm to serve as true reference. The *in vitro* samples were exposed using six CBCT units and one MSCT system. CBCT exposure protocols were chosen according to clinically available settings. The variables were kilovoltage, milliamperage, voxel size and/or scan time. Image segmentation was based on local thresholds using profile lines. The resulting jawbone segmentations were registered with the reference and image processing was done to internally fill the segmentations. A point-based distance calculation was performed between the three-dimensional objects and reference scans and deviation percentages were calculated for 2 mm, 1 mm and 0.5 mm intervals.

Results: All points of the MSCT surface models lay within a 1 mm deviation range and 98.5% within 0.5 mm compared with micro-CT. For the different CBCT systems, accuracy came close to MSCT with mean percentages of 98.9% within 1 mm deviation and 92.8% within 0.5 mm. A difference of approximately 1% between lower and upper jaws could be perceived. For the specific CBCT exposure protocols, only scan time and voxel size revealed certain significant differences.

Conclusion: Jawbone model accuracy using CBCT was comparable with MSCT. The surface models of the upper jaws deviated slightly more than those for lower jaws. CBCT exposure settings had a limited influence on accuracy with scan time and voxel size as the main factors. *Dentomaxillofacial Radiology* (2012) **41**, 466–474. doi: 10.1259/dmfr/81272805

Keywords: cone beam computed tomography; surface model accuracy; segmentation; exposure protocol

Introduction

Virtual interactive three-dimensional (3D) environments have improved the surgical planning of dental implants.^{1–3} The use of computer-manufactured surgical guides based on this 3D planning has been found to

be an accurate and reliable method to transfer the planning to the surgical field.^{4–10} However, several factors in the computerized planning as well as during guided surgery may induce errors and influence the final outcome.^{11–15} Besides clinical factors, such as drilling angulation differences owing to the tolerance of the drill in the key,^{14,15} more technical factors like the actual computer-aided manufacturing of the surgical guide or, more initially in the protocol, the acquisition of 3D images of the jawbones and radiographic

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templates may also cause errors and determine the final outcome. For mucosa-supported guides, the radiographic guide, which should be adequately positioned during scanning, will serve as the base for the surgical guide, making the procedure mainly depend on the clinical situation. But when bone-supported guides are manufactured, an adequate segmentation of the 3D data is crucial to obtain an accurate surface model which will serve as the reference base and thus will also determine the adequate fit or stability around the alveolar ridges. Although both techniques have been found to be precise and reliable solutions, some studies do point out that larger deviations are observed when using bone-supported guides.^{9,16,17}

While computer-assisted implant planning had been based on multislice CT (MSCT) for many years, cone beam CT (CBCT) provides an excellent alternative at reduced radiation dose and increased spatial resolution to depict very fine bony details.³ Although CBCT has also been found to be a reliable imaging technique for computer-guided surgery,^{16–20} jawbone segmentation quality or the accuracy of CBCT derived surface models of the jaws has only been limitedly explored.^{21,22} Furthermore, CBCT exposure parameters may influence this segmentation quality²³ and need to be thoroughly explored to establish proper clinical protocols.

The purpose of this research project was therefore to investigate the influence of exposure parameters on jawbone model accuracy when using CBCT compared with MSCT.

Materials and methods

Samples and exposure

A human edentulous upper and lower formalin-fixed jawbone (obtained with ethical approval from the Faculty of Medicine, Katholieke Universiteit Leuven, Belgium), preserved with soft tissues except for the tongue and mouth floor, were used as *in vitro* subjects. The jawbones were scanned using a micro-CT scanner, six CBCT scanners and one MSCT scanner.

For the micro-CT system, a high resolution exposure protocol (130 kV, 61 μ A, 900 ms exposure with 0.2° rotation steps, a 2240 $\times$ 2240 image size and 35 μ m image pixel size) was chosen (Skyscan 1173 high energy spiral scan micro-CT, Skyscan NV, Kontich, Belgium) in order to obtain the true reference of both upper and lower cadaver jaws. The jaws were fixed on the scan platform using foam holders and tape to avoid any movement during scanning.

An overview of the CBCT systems and exposure protocols used in this study can be found in Table 1. The cadaver jaws were scanned according to the CBCT's positioning lines (centred on the midsagittal plane and keeping the alveolar crest perpendicular to the floor). The exposure parameters for the CBCT systems were varied to determine the influence of tube current

Table 1 The cone beam CT (CBCT) systems and their exposure protocols chosen for this study

CBCT unit	Manufacturer	FOV (d $\times$ h, cm)	Tube potential (kV)	Tube current (mA)	Scan time (s)	Voxel size (mm ³)	Protocols
3D Accuitomo 170®	J. Morita Mfg. Corp., Kyoto, Japan	8 $\times$ 8	70, 80, 90	3, 4, 5	9, 16, 18, 31	0.160	12
KaVo 3D Exam®	KaVo Dental GmbH, Biberach, Germany	16 $\times$ 13	120	5	4.8, 8.9, 14.7, 26.9	0.25, 0.4	4 ^a
Promax 3D®	Planmeca Oy, Helsinki, Finland	8 $\times$ 8	84	6, 8, 10, 12	18, 26	0.2, 0.4	8 ^b
Picasso Trio®	Vatech, E-WOO Technology Co. Ltd, Gyeonggi-Do, Republic of Korea	12 $\times$ 8	75, 80, 85	4, 5, 6	15	0.2	9
Scanora 3D®	Soredex, Tuusula, Finland	10 $\times$ 7.5	85	8, 10, 12.5, 15	10, 13	0.25, 0.35	8 ^c
Iluma Elite®	Imtec Plaza, Ardmore, OK	14.2 $\times$ 21.1	120	1, 3.8	7.8, 20 and 40	0.4	6

^ad, depth; FOV, field of view; h, height.

^b4.8 s and 8.9 s corresponds to 0.4 mm voxel; 14.7 s and 26.9 s to 0.25 mm voxel.

^c18 s corresponds to 0.4 mm voxel; 26 s to 0.2 mm voxel.

^d10 s corresponds to 0.35 mm voxel; 13 s to 0.25 mm voxel.

(milliamperes), tube potential (kilovolts), scanning time and/or voxel size. Protocols were chosen depending on the commercially available settings of the specific CBCT unit. A total of 47 exposure protocols were chosen resulting in 94 CBCT scans in total (upper and lower jaw).

In a similar fashion, the cadaver jaws were scanned with an MSCT system (Somatom® Sensation 64, Siemens Medical Solutions Inc., Malvern, PA) operated at 120 kV, 48 mA and with a 0.5 mm slice thickness U75u kernel protocol (high resolution head protocol).

Image processing

The ground truth data sets using the micro-CT scans of both jaws were acquired as 16-bit tagged image file format (TIFF) images and further processed in CT-analyser (CTAn; Skyscan NV, Kontich, Belgium). First, pixel binning of 2×2 was applied to reduce the computational power. Jawbones were segmented using adaptive thresholding (Figure 1a), which was implemented in 3D and based on the mean of the minimum and maximum intensity values. The resulting binary images still showing the internal bony trabecular structures [region of interest (ROI) 1] needed to be processed in order to obtain only an outer shell of the jaws. This would allow calculation of positive as well as negative deviations from the gold standard. Therefore, a copy of ROI1 was internally filled (dilation in 2D with 3 pixels, removal of pores in 2D) and resized (erosion with 6 pixels) giving a perfectly closed but somewhat smaller (210 µm) jawbone model segmentation (ROI2; Figure 1b) for subtraction with ROI1. The subtraction of this mask created new data sets consisting of outer shells only, excluding undesired internal structures (Figure 1c). The resulting standard triangulation language (STL) files of the lower (Figure 1d) and upper jaws were then exported to serve as the reference for comparison with CBCT and MSCT.

CBCT and MSCT images of the lower and upper jaws were exported as digital imaging and communications in medicine (DICOM) files and imported into Simplant Pro Crystal® (Materialise Dental NV, Leuven, Belgium). Bone segmentation was performed using

simple thresholding. To determine the lower limit of the threshold region, five profile lines were drawn through the alveolar ridge of the jaws. For this, the axial slice at a 5 mm distance from the alveolar ridge in the midsagittal plane was chosen. The first profile line was drawn anteroposteriorly in the midsagittal region. Two additional profile lines were drawn at 5 mm and 10 mm distance to the left and right of the midsagittal line (Figure 2a). The resulting graph represents the CT intensities that can be found along these lines with two major peaks representing the cortical plates with high density values and two lower regions representing the soft tissues (Figure 2b). The average values of the two highest peaks and the two lowest regions are subtracted from each other and 30% of this outcome is then added again to the lowest average value (soft tissues). This is the chosen lower limit (threshold) for bone segmentation. Since a comparison of only the jawbone surfaces is aimed for, further processing the 3D objects was needed in the same way as the micro-CT models. Since manual segmentation would be too cumbersome in this process, we opted to use the MSCT jawbone models (less data/slices and less surface pores than the CBCT surfaces) for internal filling. In a similar fashion as with the ground truth data set, a closed and slightly eroded (two pixels) mask was created from the MSCT data set for subtraction from the original CBCT or MSCT data sets. This resulted in the final 3D objects for comparison with the ground truth data (Figure 2c).

Prior to this subtraction and 3D object calculation, the segmented jawbone models, eroded masks and ground truth models were imported into Mimics® 13 (Materialise Dental NV) in order to register the CBCT/MSCT models with the eroded MSCT masks. After subtraction, the final surface models were registered with the gold standard (micro-CT models) using a global (minimal point distance of 1 mm) followed by a local (0.5 mm as maximal distance to mask border) STL registration. Then, since the CBCT or MSCT 3D objects may not be similar in size owing to different field of view (FOV) settings, the models were cropped to leave out regions such as the mandibular ramus and

Figure 1 (a) Segmentation of the bone on a micro-CT slice. (b) Filled subregion of interest after a dilation of three pixels and erosion of six pixels. (c) Micro-CT surface model segmented by subtracting A from B, leaving an outer shell. (d) This is used to reconstruct the final surface model

Figure 2 (a) Profile lines on the axial slice of the mandible. (b) The resulting graph represents the grey values of these lines, used for the 30% calculation and final thresholding value. The latter is then used to build (c) the final surface model

only include regions relevant to implant surgery (in Magics® 13.0, Materialise Dental NV). Finally, the registered and same-sized 3D objects were imported into 3-Matic® 4.4 (Materialise Dental NV) to calculate distances between the micro-CT based reference (start) and the CBCT/MSCT surface models (end). Visual representation of these deviations was obtained using

colour maps (Figure 3) based on the deviation histograms. Three clinically relevant intervals of -2 to 2 mm, -1 to 1 mm and -0.5 to 0.5 mm were chosen for numeric interpretations by calculating the percentages of points lying within these intervals.

The ground truth segmentation of the micro-CT data was done by an experienced oral radiologist and the CBCT/MSCT segmentation by two dentists. The thresholding values obtained by the latter all showed less than 10% deviation and were averaged for further calculations. A 10% repeat of measurements at a 10-week interval revealed good observer reliability (single measures intraclass correlation coefficient of 0.79 with 95% confidence interval between 0.49 and 0.92). For the statistical analysis, CBCT/MSCT type, tube potential, tube current, voxel and/or scan time were the independent variables while the three chosen interval percentages were the dependent ones. Multiple regression analysis was done in MedCalc version 9.3.2 (MedCalc software bvba, Mariakerke, Belgium) and significance was set at 5%.

Results

Overall model accuracy

The deviations from the gold standard model for all included protocols of each CBCT system and for the MSCT system can be found in an overall bar chart (Figure 4). While for MSCT all points (100%) lay within -2 to 2 mm and -1 to 1 mm and 98.5% lay within -0.5 to 0.5 mm, mean CBCT deviations were 99.9% within -2 to 2 mm, 98.9% within -1 to 1 mm and 92.8% within -0.5 to 0.5 mm. Multiple regression analysis did not reveal any significant difference between the different CBCT/MSCT systems ($p = 0.49$) or between upper and lower jaws ($p = 0.21$). Descriptive statistics (mean, maximal and minimal percentages) for the different CBCT systems grouped by each of the three intervals can be found in Table 2.

Cone beam CT exposure parameters

The somehow larger CBCT deviations—especially for -0.5 to 0.5 mm—were further explored since many exposure protocols were included in the previous overall analysis. In the following statistical tests, each CBCT was tested for its own set of specific variables (tube potential, tube current, scan time and/or voxel size). An overview of all significant differences resulting from multiple regression models for each CBCT unit can be found in Table 3. All analyses were carried out for percentages within a combination of the three chosen intervals, namely I3 (= interval -2 to 2 mm, -1 to 1 mm and -0.5 to 0.5 mm), I2 (-1 to 1 mm and -0.5 to 0.5 mm) and I1 (-0.5 to 0.5 mm only).

Only two systems allowed varying of the tube potential parameters. Three different tube potential settings were chosen but no significant differences were

Figure 3 Example of an (a) upper and (b) lower cadaver jaw, superimposed (image registration) on their references. Deviations are colour coded with green being the corresponding point, blue the positive deviations and red the negative ones (colour illustrations can be found online)

found for Accutomo 170 (J. Morita Mfg. Corp., Kyoto, Japan) ($p = 0.8$ for I3, $p = 0.77$ for I2, $p = 0.63$ for I1) or Picasso Trio (Vatech, E-WOO Technology Co. Ltd, Gyeonggi-Do, Republic of Korea) ($p = 1$). All CBCT systems except the Kavo 3D Exam (KaVo Dental GmbH, Biberach, Germany) allowed changes to tube current to a certain extent, but no significant differences could be found for each

CBCT type. Figure 5 shows the line charts for the different scans (by jaw type and interval) at the different tube potential (above) and tube current (below) settings.

The scan time was investigated for all CBCTs except the Picasso Trio. For interval combinations I3 and I2, a significant difference was only found for Promax 3D (Planmeca Oy, Helsinki, Finland), while for I1 (only

Figure 4 Bar chart (mean) and error bars for the different cone beam CT systems, plotted by the three chosen intervals and jaw type (upper, UJ; lower, LJ)

Table 2 Summary statistics (minimal, maximal and mean percentages) for the different cone beam CT systems, plotted by the three chosen intervals

	−2 to 2 mm			−1 to 1 mm			−0.5 to 0.5 mm		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Accuitomo 170®	100	100	100	97	100	98.9	81	98	91.7
Kavo 3D Exam®	99	100	99.9	97	100	99	82	96	92.4
Iluma Elite®	98	100	99.5	94	99	97.3	77	89	83.9
Picasso Trio®	100	100	100	99	100	99.5	97	97	97
Promax 3D®	100	100	100	97	100	99.2	81	98	95.3
Scanora 3D®	100	100	100	98	100	99	83	98	94.9

Max, maximum; Min, minimum.

−0.5 to 0.5 mm) significant differences were found for Promax 3D and Iluma Elite (Imtec Plaza, Ardmore, OK), and a *p*-value of 0.1 for Scanora 3D (Soredex, Tuusula, Finland). Different voxel sizes were investigated for the Kavo 3D Exam, Promax 3D and Scanora 3D and significant differences were only found for the Promax 3D for all three intervals and a *p*-value of 0.1 for Scanora 3D for I1. Figure 6 shows the line charts for the different scans (by jaw type and interval) at the different scan time and voxel settings.

Upper and lower jaw

In general, mean deviations were 93.6% within −0.5 to 0.5 mm for the lower jaw and 92.3% for the upper jaw. Figures 5 and 6 show the line charts of percentages plotted by each jaw type. For Accuitomo 170, significant differences were found for I2 and I1 and a small *p*-value for I3 (*p* = 0.05). A small value (*p* = 0.07) was also found for Kavo 3D Exam when considering I1.

Discussion

From the overall model accuracy results, it can be concluded that MSCT has an excellent surface model accuracy. Only a minor difference for upper and lower jaw was found, with 98% and 99% of its surface points within the −0.5 to 0.5 mm deviation interval, respectively.

The different CBCT systems showed very high surface model accuracy. Although these deviations were slightly larger—especially for the −0.5 to 0.5 mm interval—no significant difference was found for any of the CBCTs compared with MSCT, even though various scanning parameters were used. Table 2 depicts minimal and maximal values which reveal that when using optimal exposure settings, the deviation percentages are similar to MSCT. No other studies could be found in the literature comparing this jawbone surface model accuracy. Loubele *et al*^{21,24,25} investigated segmentation quality of MSCT vs CBCT and found submillimetre accuracy for all scanners. Although they used another approach and investigated segmentation quality based on bone thickness measurements (linear accuracy) of dry jaws or phantoms, deviations were in the same range as found in this study. The local bone thresholding method used in this study consisted of a slightly different approach than the 50% rule previously reported by Prevrhal *et al*²⁶ and was based on internal studies of the company creating the bone supported surgical guides. However, adding 30% to the subtraction of averaged maximal and minimal intensities of the line profiles in this methodology approximated the 50% rule. All calculated threshold values were visually verified on the respective slices by the observers in case errors had occurred. Final threshold values deviated less than 10% between both observers. Furthermore, the 10% repeat of

Table 3 Overview of significant differences for each cone beam CT (CBCT) and its variables. The results are plotted for the three intervals: interval −2 to 2 mm, −1 to 1 mm and −0.5 to 0.5 mm (I3); interval −1 to 1 mm and −0.5 to 0.5 mm (I2); and interval −0.5 to 0.5 mm (I1)

Variable	Interval	CBCT					
		Accuitomo 170®	Kavo 3D Exam®	Iluma Elite®	Picasso Trio®	Promax 3D®	Scanora 3D®
Tube current (mA)	I3	<i>p</i> > 0.05	–	<i>p</i> > 0.05	<i>p</i> = 1	<i>p</i> > 0.05	<i>p</i> > 0.05
	I2	<i>p</i> > 0.05	–	<i>p</i> > 0.05	<i>p</i> = 1	<i>p</i> > 0.05	<i>p</i> > 0.05
	I1	<i>p</i> > 0.05	–	<i>p</i> > 0.05	<i>p</i> = 1	<i>p</i> > 0.05	<i>p</i> > 0.05
Tube potential (kV)	I3	<i>p</i> > 0.05	–	–	<i>p</i> = 1	–	–
	I2	<i>p</i> > 0.05	–	–	<i>p</i> = 1	–	–
	I1	<i>p</i> > 0.05	–	–	<i>p</i> = 1	–	–
Voxel	I3	–	<i>p</i> > 0.05	–	–	<i>p</i> < 0.05	<i>p</i> > 0.05
	I2	–	<i>p</i> > 0.05	–	–	<i>p</i> < 0.05	<i>p</i> > 0.05
	I1	–	<i>p</i> > 0.05	–	–	<i>p</i> < 0.05	<i>p</i> < 0.1
Scan time	I3	<i>p</i> > 0.05	<i>p</i> > 0.05	<i>p</i> > 0.05	–	<i>p</i> < 0.05	<i>p</i> > 0.05
	I2	<i>p</i> > 0.05	<i>p</i> > 0.05	<i>p</i> > 0.05	–	<i>p</i> < 0.05	<i>p</i> > 0.05
	I1	<i>p</i> > 0.05	<i>p</i> > 0.05	<i>p</i> < 0.05	–	<i>p</i> < 0.05	<i>p</i> < 0.1
Jaw type	I3	<i>p</i> < 0.1	<i>p</i> > 0.05	<i>p</i> > 0.05	<i>p</i> = 1	<i>p</i> > 0.05	<i>p</i> > 0.05
	I2	<i>p</i> < 0.05	<i>p</i> > 0.05	<i>p</i> > 0.05	<i>p</i> = 1	<i>p</i> > 0.05	<i>p</i> > 0.05
	I1	<i>p</i> < 0.05	<i>p</i> < 0.1	<i>p</i> > 0.05	<i>p</i> = 1	<i>p</i> > 0.05	<i>p</i> > 0.05

Figure 5 Line charts for the cone beam CT (CBCT) systems with variable tube potential (kV) (top) and tube current (mA) (below) settings, plotted by the three chosen intervals and jaw type (upper, UJ; lower, LJ)

measurements showed high observer reliability indicating a good reproducibility of the method.

When considering the various CBCT systems separately, analyses showed the certain influence of their specific exposure protocols. However, these results need to be interpreted carefully since these protocols (combination of variables) are often specific to a certain CBCT system. Owing to the inability to freely choose similar protocols, we explored the results for each CBCT system separately. For the Picasso Trio, the tube potential and tube current parameters were varied but did not reveal any significant differences ($p = 1$) when considering upper and lower jaws ($p = 1$). For the Accutomo 170, the three tube potential and three tube current settings did not affect significance. Similarly for all other CBCT systems where tube current settings were slightly varied, no significant effect on model accuracy could be found. Of course, these results may be owing to the fact that only a certain range of these settings could be chosen for each unit. Subtle changes seen with these variations (line charts in Figure 5) may become more important at higher or lower exposure values or for other CBCT systems. Nonetheless, for the Accutomo 170, significant differences ($p = 0.0005$ for I3, $p = 0.03$ for I2 and $p = 0.05$ for I1) were found between upper and lower jaws. The tube potential line charts in Figure 5 did show somewhat larger deviations for the upper jaw when considering the -0.5 to 0.5 mm interval at increasing tube potential (penetration level of the X-ray beams): a lower tube potential setting for the upper jaw slightly increased model accuracy. This may seem logical since the cortical borders of the upper jaw are usually thinner than those of lower jaws. When increasing the scan time for the Accutomo 170, which corresponded to an increased number of frames acquisition, no significant differences were found although the same tendency was seen for the upper jaw; increasing the scan time slightly decreased the

Figure 6 Line charts for the cone beam CT (CBCT) systems with variable (a) scan time and (b) voxel size settings, plotted by the three chosen intervals and jaw type (upper, UJ; lower, LJ)

percentage of deviations within -0.5 and 0.5 mm, which is the opposite for the lower jaw. For the Kavo 3D Exam, the variable parameters were scan time and voxel size. A voxel of 0.4 mm corresponded to a 4.7 s or 8.9 s scan time (the latter acquired double the frames), while 0.25 mm voxel corresponded to 14.7 s and 26.9 s. Line charts in Figure 6 did not show any difference for these numbers of frames per voxel but indicated a slightly increased accuracy for the upper jaw when acquiring images at a smaller voxel size, especially for deviations within -0.5 and 0.5 mm. This explains the smaller p -value ($p = 0.07$) for jaw type in Table 3. For the Iluma Elite, the voxel size was fixed at 0.4 mm, while three scan times (again with a different number of frames) were used. No difference between the upper and lower jaw was seen except for I3, where a significant difference for scan time was found ($p = 0.008$). For the Scanora 3D this difference was more subtle, but for the Promax 3D a higher scan time associated with higher number of frames and smaller voxel size did influence the accuracy for all three intervals.

From the above discussion of results, it seemed that scan time (with corresponding number of frames) and associated voxel size were more important variables with slightly larger deviations than the tube current or tube potential changes. This may be explained by the fact that these factors contribute more to a better delineation of the cortical borders and transition with surrounding soft tissues. Hassan et al²³ also investigated the influence of voxel size on 3D CBCT models of the dental arches and found smaller voxel sizes to be better. However, as seen in the line charts of Figures 5 and 6 and in Table 3, these deviations mostly affected the smallest interval (-0.5 to

0.5 mm). When considering 1 mm deviations as the clinically acceptable interval, almost no influence of exposure settings was found except for jaw type with the Accutomo 170 and voxel size/scan time with the Promax 3D. However, given the high percentages of datapoints within even the smallest intervals, it could be concluded that surface model accuracy for CBCT systems at various exposure protocols was very high and as accurate as MSCT.

Finally, although many exposure protocols were included in this study, it should be noted that for some CBCT systems, the sample size was quite small when determining the significant differences. It seemed likely that when using more cadaver samples, the differences between upper and lower jaw may increase.

Conclusion

This current research indicated clinically acceptable surface model accuracy for both MSCT and CBCT. Only slight deviations were found between the upper and lower jaw models. Exposure protocols of CBCT only influenced surface model accuracy to a minor extent, but it should be considered that higher resolution protocols (associated with increased dose levels) do not necessarily yield better 3D jawbone models.

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