American College of Cardiology/European Society of Cardiology International Study of Angiographic Data Compression Phase II

The Effects of Varying JPEG Data Compression Levels on the Quantitative Assessment of the Degree of Stenosis in Digital Coronary Angiography

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OBJECTIVES
This report describes whether lossy Joint Photographic Experts Group (JPEG) image compression/decompression has an effect on the quantitative assessment of vessel sizes by state-of-the-art quantitative coronary arteriography (QCA).

BACKGROUND
The Digital Imaging and Communications in Medicine (DICOM) digital exchange standard for angiocardiography prescribes that images must be stored loss free, thereby limiting JPEG compression to a maximum ratio of 2:1. For practical purposes it would be desirable to increase the compression ratio (CR), which would lead to lossy image compression.

METHODS
A series of 48 obstructed coronary segments were compressed/decompressed at CR 1:1 (uncompressed), 6:1, 10:1 and 16:1 and analyzed blindly and in random order using the QCA-CMS analytical software. Similar catheter and vessel start- and end-points were used within each image quartet, respectively. All measurements were repeated after several weeks using newly selected start- and end-points. Three different sub-analyses were carried out: the intra-observer, fixed inter-compression and variable inter-compression analyses, with increasing potential error sources, respectively.

RESULTS
The intra-observer analysis showed significant systematic and random errors in the calibration factor at JPEG CR 10:1. The fixed inter-compression analysis demonstrated systematic errors in the calibration factor and recalculated vessel parameter results at CR 16:1 and for the random errors at CR 10:1 and 16:1. The variable inter-compression analysis presented systematic and random errors in the calibration factor and recalculated parameter results at CR 10:1 and 16:1. Any negative effect at CR 6:1 was found only for the calibration factor of the variable inter-compression analysis, which did not show up in the final vessel measurements.

CONCLUSIONS
Compression ratios of 10:1 and 16:1 affected the QCA results negatively and therefore should not be used in clinical research studies. (J Am Coll Cardiol 2000;35:1380–7) © 2000 by the American College of Cardiology.

A few years ago the American College of Cardiology (ACC)/American College of Radiology (ACR)/National Electrical Manufacturer’s Association (NEMA) Ad Hoc Group and the European Society of Cardiology (ESC) Task Force on Digital Imaging in Cardiology (Digicare) defined standard guidelines for the digital exchange of angiographic images (1). In addition to the Digital Imaging and Communications in Medicine (DICOM) standard, the Group selected the compact disc-recordable (CD-R) as the standard interchange medium for digital angiographic images (2). To guarantee the highest image quality, the current version of DICOM allows the storage of loss free compressed data only. Using the Joint Photographic Experts Group (JPEG) compression scheme standard (3), which is available worldwide and has already established its place in medicine, this results in a maximum compression ratio (CR) of about 2:1 (4).

The total amount of image data acquired during a cardiac catheterization procedure is very large, even at a CR of 2:1. For example, a typical angiographic run acquired at 25
frames per second (frames/s), containing seven cardiac cycles and assuming a heart rate of 80 beats/min, would require $512^2 \times 8 \times 25 \text{ frames/s} \times 7 \text{ cardiac cycles} \times 60/80 \text{ s/beat} = 34.4 \text{ megabytes (MB)}$ of memory. When the angiographic procedure consists of a total of six coronary angiographic runs and two left ventricular angiographic runs, this procedure would require about 275 MB of image data. At a CR of 2:1, this amount can be reduced only to 138 MB. A data reduction of this size is not enough to overcome the considerable limitations of large storage requirements, long image transmission times, and difficulty in replaying coronary angiograms in real time directly from a CD-R (4,5).

A simple and cheap way to overcome these limitations is to increase the CR. However, at increased JPEG CRs, this technique becomes lossy, and visible distortions may appear in the images—the so-called block artifacts. In addition, the diagnosis may be hampered, as well as the derivation of quantitative results by quantitative coronary arteriography (QCA). Because the classification of loss free (CR $\leq 2:1$) and lossy compression (CR $> 2:1$) is based on physical-mathematical considerations instead of physiological-clinical considerations (4), research has focused predominantly on the visual image quality for CRs higher than 2:1.

Silber et al. (4) found that CRs of 5:1 and 6:1 do not lead to clinically relevant deterioration of the image quality. Breeuwer et al. (6,7) reported that clearly visible block artifacts appear at CRs beyond 8:1, while Baker et al., Rigolin et al. and Slump et al. (8–10) reported that even a CR of 15:1 or 16:1 does not alter the diagnostic assessment of lesion severity and the clinical decision making. Therefore, a modification of the existing guidelines to allow higher CRs was suggested.

But how do these CRs affect the results of QCA? Based on results from an earlier QCA pilot study, Koning et al. (11,12) concluded that the use of CRs of 5:1 or higher should be discouraged for QCA. Contrary to the idea that QCA will be the limiting factor in the possible approval of an increase of the CR in the guidelines, Whiting et al. (5) reported that visual image quality rather than QCA accuracy will be the limiting criterion for lossy image compression of digital coronary angiograms.

To help clarify these contradictory perceptions and to obtain objective data about errors attributable to lossy data compression, from both a visual interpretation and a QCA point of view, a large controlled study, the International Compression Study (ICS) was designed and carried out with the support of the ACC and the ESC. This study consists of three phases: Phase I, dealing with the effect of JPEG image compression on the diagnostic interpretation of images (13); Phase II, dealing with the results of QCA measurements (this article); and Phase III, dealing with the image quality (14). The goal of Phase II was to investigate whether JPEG image compression/decompression has an effect on the quantitative assessment of vessel sizes by state-of-the-art QCA. The JPEG CRs investigated were 1:1 (no compression), 6:1, 10:1 and 16:1.

**MATERIALS AND METHODS**

**Patient data.** From the total data set ($n = 100$ runs) of the ICS, runs were selected by an expert reader at Heart Core BV (Leiden, The Netherlands) for later QCA. Selection criteria required among others that each obstruction was well visualized (well-filled with contrast dye and no overlap with other major vessels). Also, images of totally occluded coronary arteries and arteries with only an irregular lesion with a visual percentage diameter stenosis smaller than 20% were excluded from this selection. In at least one frame of the run, a non-tapering part of the contrast catheter had to be visible over a length of at least 1 cm for calibration purposes. As a result of this initial selection process, a total of 58 angiographic runs remained. It should be noted that the 100 angiographic runs in the ICS in general had not been acquired according to QCA acquisition guidelines.

Next, final frame selection according to the QCA criteria was carried out by the same expert reader. Frame selection criteria included a preference for end-diastolic frames, obstructions that are free from overlaps with other vessels, vessels that are well-filled with contrast agent and suitability for catheter calibration. As a result of this selection process, the QCA data set was reduced to 45 frames with 50 lesion sites. Of these, five frames had two lesion sites. The selected frames were compressed and subsequently decompressed at the University of Kiel, Germany (Tim Becker, Rüdiger Simon) using the JPEG scheme at CRs of 1:1 (no compression), 6:1, 10:1 and 16:1, hereafter generally denoted as CR 1, 6, 10 and 16. The JPEG compression/decompression procedure was performed using public domain Portable...
Video Research Group-JPEG software using default quantization tables. After decompression, the sequences of the image quartet per run (original, CR 6, CR 10 and CR 16) were written in random order to a CD-R in DICOM files (raw data format, 512 × 512 pixels, 8-bit depth and no header).

**QCA.** All the QCA measurements were carried out with the Cardiovascular Measurement System (QCA-CMS Version 3.32, MEDIS medical imaging systems, Leiden, The Netherlands). The basic algorithms have been described elsewhere (15,16). For a digital application with the images stored in DICOM format on a CD-R, the regions of interest (ROIs) of size 256 × 256 pixels encompassing the catheter and the coronary segment were extracted from the digital matrix data and digitally zoomed by a factor of 2 to a full matrix size (512 × 512 × 8 bits) using an interpolation scheme.

The research version of the QCA-CMS package that was used in this study allows in addition the readout (and re-entrance) of the coordinates of the start- and end-points of the analyzed segments, so that exactly the same vessel segments could be analyzed in the corresponding images of the image quartet.

**Standardized analysis protocol.** To be able to compare the quantitative measurements of the arterial segments in corresponding images, which differ only in CRs, a standardized approach was followed. Because the study images were blinded to the QCA technician, one image of each image quartet (original, CR 6, CR 10 and CR 16) was analyzed first. The start- and end-points of the pathlines were manually positioned in these images at the major bifurcations proximally and distally to the obstruction to be analyzed. These start- and end-points were recorded and re-used in the other three images of the corresponding image quartet (at time t0). After an interval of a few weeks (at time t1), all images were re-analyzed by the same QCA technician with the same protocol to assess the intra-observer difference. This technician had no information whatsoever at this time (t1) about the results from the first procedure (t0).

The calibration procedure was performed on the basis of the catheter, before every measurement, with the same standardized protocol as described for the arterial segments.

The measured parameters that were compared in this evaluation study were the absolute obstruction and reference diameter, the percentage diameter stenosis, the mean segment diameter, the segment length of the entire analyzed arterial segment and the calibration factor. Three series of comparisons were carried out on the mentioned parameters (Fig. 1):

- **Intra-observer analysis:** For the original series (CR 1) as well as for the three compressed/decompressed series (CR 6, 10 and 16), the mean signed differences (accuracy or systematic error) between the values of the first (t0) and repeated measurements (t1), and the standard deviation of these differences (precision or random error), were calculated to express the intra-observer difference for each of the four series. In this way, the influence of a repeated measurement with different start- and end-points of the segments can be assessed for the different CRs.

![Figure 1](image1.png)

**Figure 1.** The three series of comparisons performed in this study. a) The fixed inter-compression analysis and the intra-observer analysis, b) the variable inter-compression analysis.
Table 1. Intra-Observer Analysis Between the Repeated (t 1) and First (t 0) Calibrations of 48 Catheters in the Original and the Compressed/Decompressed (CR 6, 10 and 16) Image Series

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>n = 48</th>
<th>Original (t 1) vs. Original (t 0)</th>
<th>CR 6 (t 1) vs. CR 6 (t 0)</th>
<th>CR 10 (t 1) vs. CR 10 (t 0)</th>
<th>CR 16 (t 1) vs. CR 16 (t 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration factor (mm/pixel)</td>
<td>0.0001 ± 0.0021</td>
<td>−0.0003 ± 0.0023</td>
<td>0.0015* ± 0.0033†</td>
<td>−0.0005 ± 0.0025</td>
<td></td>
</tr>
</tbody>
</table>

Data are presented as systematic error ± random error. Systematic error: *overall p < 0.0005; Random error: †p < 0.01.

- **Fixed inter-compression analysis**: For each of the CRs the mean signed differences between the values of the first measurements in the original images (t 0) and the first measurements in the compressed/decompressed images (t 0), and the standard deviation of these differences, were calculated to express the fixed inter-compression difference. In this way, one can assess the influence of only the different CRs with unchanged user interaction.

- **Variable inter-compression analysis**: The mean signed differences between the values of the first measurements in the original images (t 0) and the repeated measurements in the uncompressed and the compressed/decompressed images (t 1), and the standard deviation of these differences, were calculated to express the variable inter-compression difference for each CR. In this way, the combined influence of a higher CR and a repeated measurement becomes apparent.

The three types of comparisons are displayed schematically in Figure 2.

**Statistical analysis.** The “mixed model” analysis of variance was used to determine the significance of the differences in the systematic errors derived from the three different analytical approaches (level of significance α = 0.05).

The Levene’s test was used to determine the significance of the differences in the random errors (in other words, the homogeneity of variances) of the variable inter-compression analysis and of the intra-observer analysis (level of significance α = 0.05).

Because of the high dependency of all the first measurements (identical start- and end-points) used to determine the fixed inter-compression differences (Tables 3 and 4), we used another method to analyze these differences in the random errors. We tested the hypothesis of the equality of the variance of the difference between CR 6 and original (t 0) (say x) and the variance of the difference between CR 10 and the original (t 0) (say y) by testing whether the Pearson’s correlation between x + y and x – y was zero. If that is the case, we can show that $\sigma^2_x = \sigma^2_y$ (level of significance α = 0.05).

**RESULTS**

In only two of the 45 image quartets, manual editing to the otherwise automatically detected contours was felt necessary. For reasons of excluding any possible influence of manual editing on the compression study, it was decided to exclude these two image quartets from the QCA study. As a result, all the data were based on 43 image quartets (48 lesion sites) with automatically detected contours and without any manual editing.

The results are presented separately for the calibration factor (Tables 1, 3, 5) and the vessel parameter measurements. Clearly, image compression can have an effect on vessel measurements in two ways: 1) indirectly, through the measured calibration factor, and 2) directly, through the vessel contour detection. To exclude the indirect influences of the CR through the calibration factor, all vessel measurements were recalculated using the corresponding calibration factor that was found for the original image (t 0) (Table 2, 4, 6). For the variable inter-compression analysis, which represents a combination of the two analyses, the parameter values are also presented as originally measured (i.e., with the calibration factor associated with each particular frame) (Table 7). This allows us to study the total influence of the CR on the QCA measurements.

Table 2. Intra-Observer Analysis Between the Repeated (t 1) and First (t 0) Measurements of 48 Coronary Obstructions in the Original and the Compressed/Decompressed (CR 6, 10 and 16) Image Series

<table>
<thead>
<tr>
<th>Measured Parameter n = 48</th>
<th>Original (t 1) vs. Original (t 0)</th>
<th>CR 6 (t 1) vs. CR 6 (t 0)</th>
<th>CR 10 (t 1) vs. CR 10 (t 0)</th>
<th>CR 16 (t 1) vs. CR 16 (t 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obstruction diameter (mm)</td>
<td>0.02 ± 0.11</td>
<td>−0.03 ± 0.13</td>
<td>0.01 ± 0.11</td>
<td>−0.01 ± 0.15</td>
</tr>
<tr>
<td>Reference diameter (mm)</td>
<td>−0.01 ± 0.09</td>
<td>0.00 ± 0.11</td>
<td>−0.01 ± 0.11</td>
<td>−0.03 ± 0.11</td>
</tr>
<tr>
<td>Percentage diameter stenosis (%)</td>
<td>−0.85 ± 3.71</td>
<td>0.97 ± 3.85</td>
<td>−0.56 ± 3.99</td>
<td>−0.31 ± 5.47</td>
</tr>
<tr>
<td>Mean segment diameter (mm)</td>
<td>0.02 ± 0.15</td>
<td>0.01 ± 0.15</td>
<td>0.02 ± 0.16</td>
<td>0.01 ± 0.18</td>
</tr>
<tr>
<td>Segment length (mm)</td>
<td>−0.24 ± 2.16</td>
<td>0.06 ± 2.17</td>
<td>−0.07 ± 2.07</td>
<td>−0.05 ± 2.20</td>
</tr>
</tbody>
</table>

All data were recalculation with the calibration factor found for the original (t 0), to exclude possible additional influences of the compression ratio through the calibration factor, and are presented as systematic error ± random error.
The intra-observer analysis. In the first column of Tables 1 and 2, the intra-observer differences for the most relevant parameters—calibration factor (Table 1), obstruction diameter, reference diameter, percent diameter stenosis, mean segment diameter and the segment length—as assessed from 48 coronary obstructions in the uncompressed images (CR 1 vs. 1 [t1 vs. t0]) are presented. All the systematic errors in this column were very small and corresponded very well with the intra-observer data presented in earlier studies (12,17). The random error in the calibration factor was 0.0021 mm/pixel, which was smaller than the corresponding variability observed in another study (0.005 mm/pixel) (17). All the other random errors were small and of a magnitude comparable to that observed elsewhere (12,17).

In the other three columns of Tables 1 and 2, the intra-observer differences are presented for the same parameters, as measured in the series with different CRs (CR 6 vs. 6, 10 vs. 10 and 16 vs. 16 [t1 vs. t0]). The systematic errors for the calibration factor at different CRs continue to be very small; only at CR 10 vs. 10 (t1 vs. t0) was the error of 0.0015 mm/pixel significant (overall \( p < 0.0005 \)). The same was true for the random error in the calibration factor at CR 10 vs. 10 (t1 vs. t0) \( (p < 0.01) \). The systematic and random errors for all the other parameters were not significantly different.

The fixed inter-compression analysis. In Tables 3 and 4, the fixed inter-compression differences—i.e., the differences between the results obtained from the first measurements in the compressed/decompressed images \( (t_0) \) with respect to the corresponding measurements in the original images \( (t_0) \)—are presented for the different CRs (CR 6 vs. 1, 10 vs.

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>CR 6 ( (t_0) ) vs. Original ( (t_0) )</th>
<th>CR 10 ( (t_0) ) vs. Original ( (t_0) )</th>
<th>CR 16 ( (t_0) ) vs. Original ( (t_0) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration factor (mm/pixel)</td>
<td>0.0003 ± 0.0023</td>
<td>0.0004 ± 0.0033†</td>
<td>0.0020‡ ± 0.0040‡</td>
</tr>
<tr>
<td>Reference diameter (mm)</td>
<td>0.03 ± 0.13</td>
<td>0.04 ± 0.18†</td>
<td>−0.01 ± 0.16</td>
</tr>
<tr>
<td>Obstruction diameter (mm)</td>
<td>−0.01 ± 0.11</td>
<td>0.00 ± 0.10</td>
<td>0.03 ± 0.13</td>
</tr>
<tr>
<td>Percent diameter stenosis (%)</td>
<td>−1.37 ± 5.21</td>
<td>−1.45 ± 6.77†</td>
<td>1.02† ± 6.84</td>
</tr>
<tr>
<td>Mean segment diameter (mm)</td>
<td>0.01 ± 0.06</td>
<td>0.01 ± 0.06</td>
<td>0.01 ± 0.07</td>
</tr>
<tr>
<td>Segment length (mm)</td>
<td>−0.05 ± 0.41</td>
<td>0.08 ± 0.40</td>
<td>0.00 ± 0.57†</td>
</tr>
</tbody>
</table>

All data were recalculated with the calibration factor found for the original \( (t_0) \), to exclude possible additional influences of the compression ratio through the calibration factor, and are presented as systematic error ± random error. Systematic error: †overall \( p < 0.05 \); Random error: ‡\( p < 0.05 \).
Table 5. Variable Inter-Compression Analysis Between the Repeated Calibrations (t₁) of 48 Catheters in the Original and the Compressed/Decompressed (CR 6, 10 and 16) Image Series and the First Calibrations (t₀) in the Original Image Series

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>Original (t₀) vs. Original (t₁)</th>
<th>CR 6 (t₁) vs. Original (t₀)</th>
<th>CR 10 (t₁) vs. Original (t₀)</th>
<th>CR 16 (t₁) vs. Original (t₀)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration factor (mm/pixel)</td>
<td>0.0001 ± 0.0021</td>
<td>0.0001 ± 0.0030 *</td>
<td>0.0019† ± 0.0037‡</td>
<td>0.0014* ± 0.0038§</td>
</tr>
</tbody>
</table>

Data are presented as systematic error ± random error. Systematic error: *overall p < 0.005; †overall p < 0.0005; Random error: ‡p < 0.05; §p < 0.005.

(t₁ vs. t₀) and the percentage diameter stenosis at CR 16 vs. 1 (t₁ vs. t₀). The random errors for the calibration factor increased from 0.0021 to 0.0038 mm/pixel with the use of higher CRs (all p-values < 0.05). Only the random errors for both the obstruction diameter and percentage diameter stenosis at CR 10 vs. 1 and 16 vs. 1 (t₁ vs. t₀) were statistically different (p-values < 0.05).

Finally in Table 7, the non-recalculated parameter results of the variable inter-compression analyses are presented as well, to see what the total influence of the CR on the calibration factor and the parameter measurements combined was. The variable inter-compression systematic error parameters were all small, yet statistically different, for their systematic errors at CR 10 vs. 1 and 16 vs. 1 (t₁ vs. t₀), except for the obstruction diameter at CR 16 vs. 1 (t₁ vs. t₀) and the percentage diameter stenosis at CR 10 vs. 1 (t₁ vs. t₀) (overall p > 0.05). The random errors in the obstruction diameter, reference diameter and percentage diameter stenosis all had p-values < 0.05 at CR 10 vs. 1 and 16 vs. 1 (t₁ vs. t₀).

**DISCUSSION**

In this article we describe the results of Phase II of the ICS, which was carried out to examine the effects of lossy data compression on the results of QCA, using the JPEG data compression scheme at CRs 1 (no compression), 6, 10 and 16. For this purpose we have used the QCA-CMS analytical software package (version 3.32). It should be noted that other QCA analytical packages may lead to other results (5).

The outcome of QCA measurement results depends on two factors: the calibration factor used and the vessel contour delineation. Because the calibration factor is also derived through an automated contour detection process on the QCA-CMS, it is possible that a particular CR affects both the calibration and the coronary vessel contour detection procedures. For that reason, we have first assessed the effects of the JPEG compression technique on these factors separately, followed by an analysis of the combined effect.

**The influence of the CR on the calibration factor.** Statistical differences were found for the systematic and random errors during all three types of analyses (Tables 1, 3 and 5). Because the variable inter-compression analysis represents a combination of the intra-observer and fixed inter-compression analyses, it was not unexpected that the largest effects would be found within this analysis. Differences began to appear at CR 6 for the random errors and at CR 10 for the systematic errors. Thus, the catheter calibration process itself was indeed influenced by the CR applied to the images.

**The influence of the CR on coronary vessel contour detection.** Joint Photographic Experts Group compression did not present any adverse effects on the outcomes (systematic or random errors) of the vessel contour detection measurements as part of the intra-observer analysis (Table 2). Because this type of analysis concerns only a repeated vessel contour detection measurement, this finding was expected. Furthermore, these results also correspond with the data ranges found in earlier intra-observer studies (18). Regarding the fixed and variable inter-compression analyses, JPEG compression did show some significant influences (Tables 4 and 6). Significant over-estimations were found for the percentage diameter stenosis at CR 16 vs. 1 (t₀ vs. t₁) and (t₁ vs. t₀) and the obstruction diameter at CR 10 vs. 1.
CR 10 vs. 1 and 16 vs. 1 (t1 vs. t0). The found alterations can add additional systematic errors in various vessel parameters at diameter at CR 10 vs. 1 and 16 vs. 1 (t1 vs. t0) and six statistically significant systematic and random errors are found. The results (Table 6), clearly demonstrates that additional statistical significant and random errors are found. We want to thank Hein Koops, BSc, from Heart Core BV for database management support.

### Table 7. Variable Inter-Compression Analysis Between the Repeated Measurements (t1) of 48 Coronary Obstructions in the Original and the Compressed/Decompressed (CR 6, 10 and 16) Image Series and the First Measurements (t0) in the Original Image Series

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>n = 48</th>
<th>Original (t0) vs. Original (t0)</th>
<th>CR 6 (t1) vs. Original (t0)</th>
<th>CR 10 (t1) vs. Original (t0)</th>
<th>CR 16 (t1) vs. Original (t0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obstruction diameter (mm)</td>
<td>0.02 ± 0.11</td>
<td>-0.01 ± 0.13</td>
<td>0.08‡ ± 0.18§</td>
<td>0.00 ± 0.18#</td>
<td></td>
</tr>
<tr>
<td>Reference diameter (mm)</td>
<td>-0.01 ± 0.10</td>
<td>-0.01 ± 0.14</td>
<td>0.06† ± 0.17</td>
<td>0.05* ± 0.16</td>
<td></td>
</tr>
<tr>
<td>Percentage diameter stenosis (%)</td>
<td>-0.85 ± 3.71</td>
<td>-0.40 ± 4.93</td>
<td>-2.01 ± 6.59</td>
<td>0.70^ ± 8.15#</td>
<td></td>
</tr>
<tr>
<td>Mean segment diameter (mm)</td>
<td>0.03 ± 0.16</td>
<td>0.02 ± 0.19</td>
<td>0.09± ± 0.19</td>
<td>0.07± ± 0.22</td>
<td></td>
</tr>
<tr>
<td>Segment length (mm)</td>
<td>-0.19 ± 2.12</td>
<td>0.05 ± 2.23</td>
<td>0.59± ± 2.15</td>
<td>0.42± ± 2.14</td>
<td></td>
</tr>
</tbody>
</table>

Data are presented as systematic error ± random error. Systematic error: *overall p < 0.05; †overall p < 0.01; ‡overall p < 0.005; §overall p < 0.0005; Random error: [p < 0.05; ¶p < 0.01; #p < 0.005.

The influence of the CR on the calibration factor and the coronary vessel contour detection combined. The preceding text showed that an increasing CR had a significant influence on the random and systematic errors of the calibration factor and of a number of derived vessel parameters. In practice, of course, these two factors are combined. To assess the most useful information without getting lost in unnecessary details, the combined effect of the calibration factor and the vessel contour detection is presented only for the variable inter-compression analyses. Comparing these study results (Table 7) with the earlier discussed recalculated results (Table 6), clearly demonstrates that additional statistically significant systematic and random errors are found. These include two additional random errors in the reference diameter at CR 10 vs. 1 and 16 vs. 1 (t1 vs. t0) and six additional systematic errors in various vessel parameters at CR 10 vs. 1 and 16 vs. 1 (t1 vs. t0). The found alterations can be ascribed only to the individual calibration factors that were used. Studying these individual calibration factors (Table 5) clearly demonstrates that the significant systematic and random errors occur at CRs similar to the ones for the additional vessel parameter errors (Table 7). Clearly, these calibration factor errors had a significant influence on the parameter results. An exception to this rule is the calibration factor random error at CR 6 vs. 1 (t1 vs. t0) in Table 5 (p < 0.005), which does not correspond with any additional parameter error at CR 6 vs. 1 (t1 vs. t0) (Table 7).

From the preceding text, it is clear that most of the significant differences found resulted from the influence of the CR on the calibration factor. The explanation for this high degree of influence on measurement results is quite evident: any absolute vessel diameter or length measurement result is obtained by multiplying the calibration factor with the number of pixels measured between contours or along a vessel segment.

In this study we found statistically significant differences in the variability of the QCA parameter measurements, especially with the use of CRs 10 and 16. However, one should consider whether these differences are indeed relevant for daily clinical decision making and patient care in the individual patient. As an example, consider a longitudinal clinical research study with two images of one patient acquired over a certain period of time. Can we unmistakably declare whether the underlying coronary artery disease progressed, regressed or remained stable over the study period? This situation is best illustrated by the obstruction diameter results of the variable inter-compression analysis (Table 7). Taking into account a 95% confidence interval (CI) of the random error, the threshold of the significance level for an individual obstruction will alter from ±0.22 mm (2 × SD; uncompressed images) to ±0.36 mm, when at follow-up CR 10 was used. This means that at CR 10 a change in the obstruction diameter must become an additional 64% larger to be statistically significant. With the use of CR 6, the threshold change will increase by 18% (95% CI of the random error is ±0.26 mm), which is much smaller and consequently will reveal relevant differences earlier than CR 10.

### CONCLUSIONS

In conclusion, ICS Phase II—testing the effect of the JPEG data compression scheme at three different CRs (6, 10 and 16) on the QCA measurements—shows that significant systematic and random differences in the calibration factor and vessel measurements occur at CR 10 and 16. Any negative effect at CR 6 was found only for the calibration factor of the variable inter-compression analysis, which did not show up in the final vessel measurements. Therefore, it is not advisable to use CR 10 and 16 in QCA studies. Because CR 6 results in some higher measurement variabilities, these should be regarded with care in the assessment of changes in vessel morphology in the individual patient.

### Acknowledgments

We want to thank Hein Koops, BSc, from Heart Core BV for database management support.

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