Mimics® Innovation Suite

Mimics® Centerline Extraction: Quantitative Validation

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Introduction

For both cardiovascular and pulmonology applications, tubular structures such as the bronchial tree, and arteries need to be characterized. Typically, a centerline of these tubular structures is extracted before correct measurements, and associated views can be obtained (Bouix *et al.*, 2004, Choi *et al.*, 2002, Jiang and Gu, 2005, Schaap *et al.*, 2009, Wan *et al.*, 2002). An automated centerline extraction, with manual adjustment possibilities of the centerline control points is implemented in Mimics 15.0 and 16 (Materialise N.V., Belgium). This white paper describes the quantitative validation of this centerline extraction method.

Materials and methods

1. Synthetic objects based on reference centerline

The quantitative validation of the centerline extraction was based on the method described by Bouix *et al.* (2004). First, reference centerlines were created in 3-matic (Materialise N.V., Belgium), both analytical ones, and a freeform one, based on a combination of splines. Starting from these reference centerlines, synthetic 3D objects were created in 3-matic (Materialise N.V., Belgium). Different types of such synthetic objects were designed to analyze the centerline extraction behavior in different geometries, and under the influence of different noise levels. In accordance with the research of Bouix *et al.* (2004), the following reference centerlines, and associated synthetic objects were created (Figure 1 and Table 1):

- *Tube*: a straight centerline, and a tubular synthetic object with constant radius
- *Sine Tube*: a sinusoidal centerline, and a sinusoidal synthetic object with constant radius
- *Sausage*: a straight centerline, and a sausage like synthetic object with varying radius
- *Helix*: a helical centerline, and a helical synthetic object with constant radius
- *Tree*: a tree structure based on a combination of splines, and a tree like synthetic object with constant radius

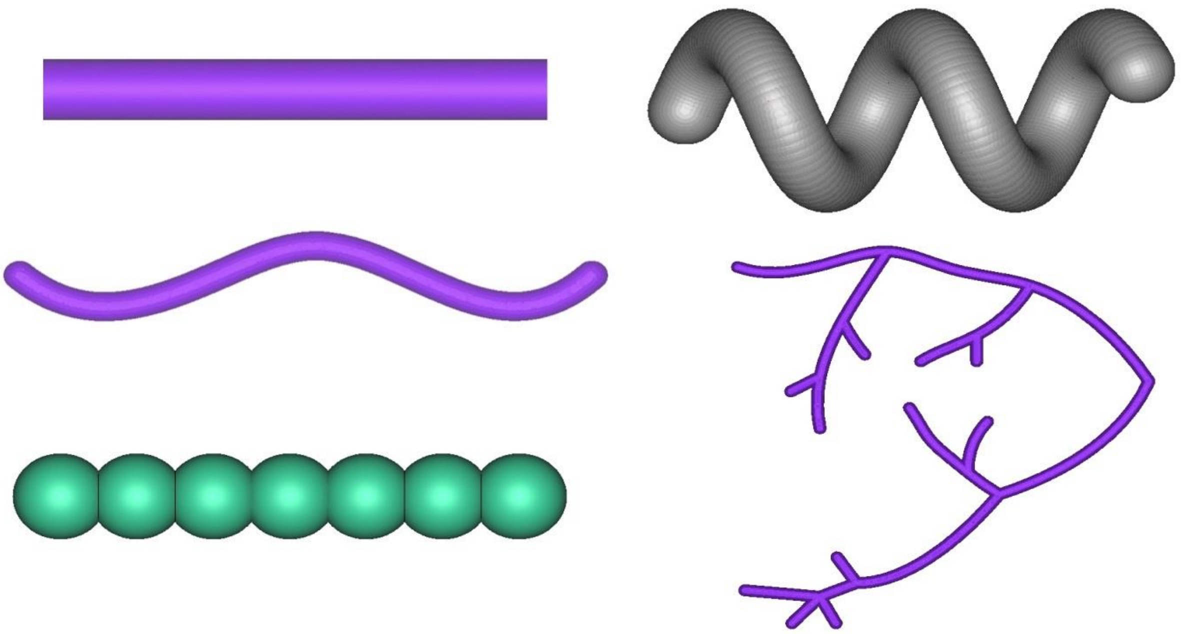

Figure 1: The different synthetic models created for the centerline extraction validation: Tube model, Sine tube model, Sausage model, Helix model, and Tree model.

In this way, the behavior was evaluated under variations in curvature (Sine Tube), in cross section diameter (Sausage), and in torsion and curvature (Helix). The extraction of a centerline in branching structures was evaluated through the tree object (Tree).

Moreover, to all these objects, different levels of noise were added (Figure 2):

- *No noise*
- *Gaussian noise with standard deviation SD = 20*, representative of the noise level in MR and CT data (Aylward and Bullitt, 2002)
- *Gaussian noise with standard deviation SD = 40*, representative of the noise level in ultrasound data (Aylward and Bullitt, 2002)
- *Gaussian noise with standard deviation SD = 80*, representative of worst case data (Aylward and Bullitt, 2002)

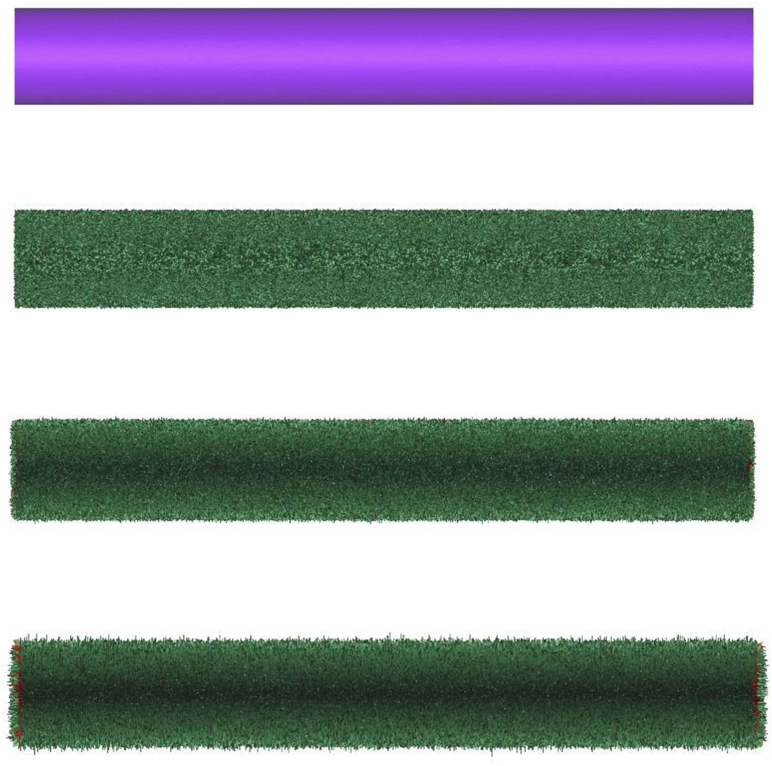

Figure 2: Tube model with several levels of noise: no noise, noise with SD 20, noise with SD 40, and noise with SD 80.

Table 1: Overview of the model characteristics

	Radius	*Length*	*Evaluation of CL behaviour under variations in*	*Validation for (examples)*
Tube	20 mm	300 mm		Ascending aorta
Sine tube	5 mm	188 mm	Curvature	Iliac arteries with curvature (0.04/mm)
Sausage	30 mm (largest) 17.7 mm (smallest)	300 mm	Cross section diameter	Aorta with aneurysms and stenosis (until 41 % difference in diameter)
Helix	7.5 mm	90 mm	Curvature and Torsion	Iliac arteries with curvature and torsion (tortuosity of 1 loop: 0.60)
Tree	4.5 mm	/	Branching	Iliac arteries with branches

2. Correspondence reference and extracted centerline

All these objects were loaded into a Mimics project to be able to extract the centerline via the algorithm implemented in Mimics 15.0 (Materialise N.V., Belgium). This automatically extracted centerline could then be further improved by manual adjustments of the control points and the branching points if necessary. The correspondence between the reference and the extracted centerline was calculated following the method described by Schaap *et al.* (2009), which was implemented in 3-matic (Materialise N.V., Belgium). Both centerlines were discretized into a number of segments of equal length chosen by the operator. This discretization leads to a number of equidistant points on both centerlines which were used for a point-to-point correspondence quantification based on the Euclidean distance.

The length chosen for the segments was 0.3 mm. Based on the current common resolution of a cardiovascular scan of 0.6 mm, this segment length of 0.3 mm for the comparison of both centerlines will ensure a segment per pixel following the Nyquist/Shannon theorem.

Additionally, the correspondence between both centerlines was visualized by connection lines between points of both centerlines (Figure 3).

The distance between both centerlines per segment was determined as the length of the median of the triangle formed by a point on one centerline, and the corresponding segment on the other centerline (Figure 3). So, the average and median distance could be calculated, and compared with some specific threshold (for example 0.6 mm, the most common resolution of current cardiovascular scans).

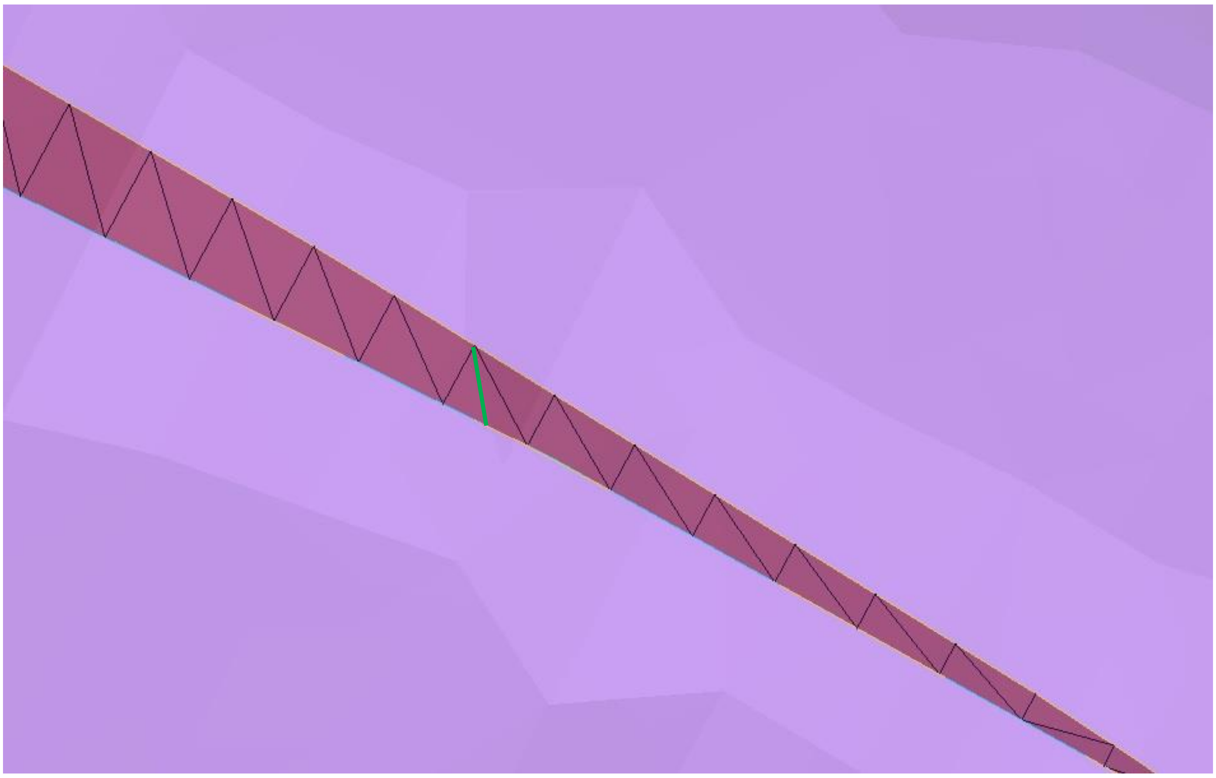

Figure 3: Visualization of the correspondence between both centerlines by connection lines between points of both centerlines. The distance between both centerlines per segment was determined as the length of the median of the triangle formed by a point on one centerline, and the corresponding segment on the other centerline (shown in green).

3. Comparisons

The following comparisons were made concerning the deviation of the extracted CL from the reference CL.

Comparisons of centerline extraction behavior:

1. Differences between the models without noise (centerline extracted in Mimics 15.0 with default values)
   → Test the differences in performance of the centerline extraction under different levels of narrowing, curvature and torsion, in the absence of noise
2. Differences between the models with noise SD 20 (centerline extracted in Mimics 15.0 with default values)
   → Test the differences in performance of the centerline extraction under different levels of narrowing, curvature and torsion, in the presence of normal levels of noise
3. Differences between the models without noise and with noise (centerline extracted in Mimics 15.0 with default values)
   → Test the differences in performance of the centerline extraction under different levels of noise
4. Differences between the centerlines with no smoothing and with smoothing (models with noise SD 20, CL extracted in Mimics 15.0 with default smooth factor and with smooth factor=0)
   → Test the performance of the centerline smoothing when normal levels of noise are present
5. Differences between the centerlines with no smoothing and with smoothing (models with noise SD 40, CL extracted in Mimics 15.0 with default smooth factor and with smooth factor=0)
   → Test the performance of the centerline smoothing when higher levels of noise are present
6. Differences between the centerlines with no smoothing and with smoothing (models with noise SD 80, CL extracted in Mimics 15.0 with default smooth factor and with smooth factor=0)
   → Test the performance of the centerline smoothing when extreme high levels of noise are present

Results and discussion

In this section, all median distances (in mm) between the extracted centerline and the reference centerline are compared with each other. The average was not chosen, as large deviations near the endings of the centerline may influence the average value strongly.

Because the models have different radii, the relative median distances are calculated as the ratio of the median distance (in mm) to the radius of the model (in mm).

As background information, some information on the centerline extraction in Mimics and its parameters is given below.

1. Centerline extraction

The centerline extraction method in Mimics consists of three parts, namely (1) a centerline extraction, (2) a centerline smoothing algorithm, and (3) a centerline fitting algorithm.

The centerline smoothing deploys a Fourier smoothing method which removes high frequency noises from the initial centerline. The level of smoothing is determined by a threshold, which is dependent on the branch size. Therefore, smoothing will be different in the different branches. The smoothing stops when at least one point in the branch of the centerline deviates from its original position more than the threshold (mm) = (smooth factor) * (average branch radius). The smooth factor can be adjusted via the slider in the centerline fit dialog.

The centerline extraction algorithm defines the center of the anatomy. The user can influence two parameters of this algorithm, namely the ‘resolving resolution’ and the ‘distance between control points’.

The ‘resolving resolution’ indicates the size of the tubular structure which will be recognized by the algorithm, and of which the centerline will be extracted. A smaller resolving resolution (in mm) will allow the extraction of a centerline in tubular structures with a smaller diameter. A higher resolving resolution (in mm) will decrease the amount of small vessels, detail or noise recognized by the algorithm, and therefore the creation of a centerline in these details.

The ‘distance between control points’ parameter sets the distance between two successive control points between which the centerline is interpolated. A smaller distance between control points (in mm) will allow the extraction of a centerline which follows more closely the geometry changes over the tubular structure. For tubular structures with a smaller diameter, a smaller distance between the control points should be used to capture all details.

The centerline extraction algorithm automatically detects the detail in the geometry and sets the values of those two critical parameters. However, if the user is not pleased with the result, the parameters can be set manually.

In Mimics 14, 15, and 16 the final fitting of the centerline is done with a quadratic spline interpolation. In Mimics 17.0, the user is able to choose between a quadratic or a cubic spline interpolation. This choice will influence the measurements made on the centerline, more specifically the curvature and the triad measurement. Those two measurements are highly sensitive to the degree of spline interpolation as both are defined by the first and second derivative of the final spline.

2. Comparisons: results & discussion

In the sections below, the different comparisons described above are evaluated.

2.1. Differences between the models without noise

To evaluate the effect of curvature, tortuosity, changing diameter, and branching on the centerline extraction, the deviation of the default extracted centerline to the reference centerline is compared between the different models without noise.

The standard deviation can be very high, for example in the Tube model. This results from the fact that the centerline deviates towards the vessel wall at the end of the vessel or model (Figure 4). Therefore, (1) the median distance, and (2) the 80th percentiles are calculated, and shown in the tables below (Table 2, Table 3, and Table 4).

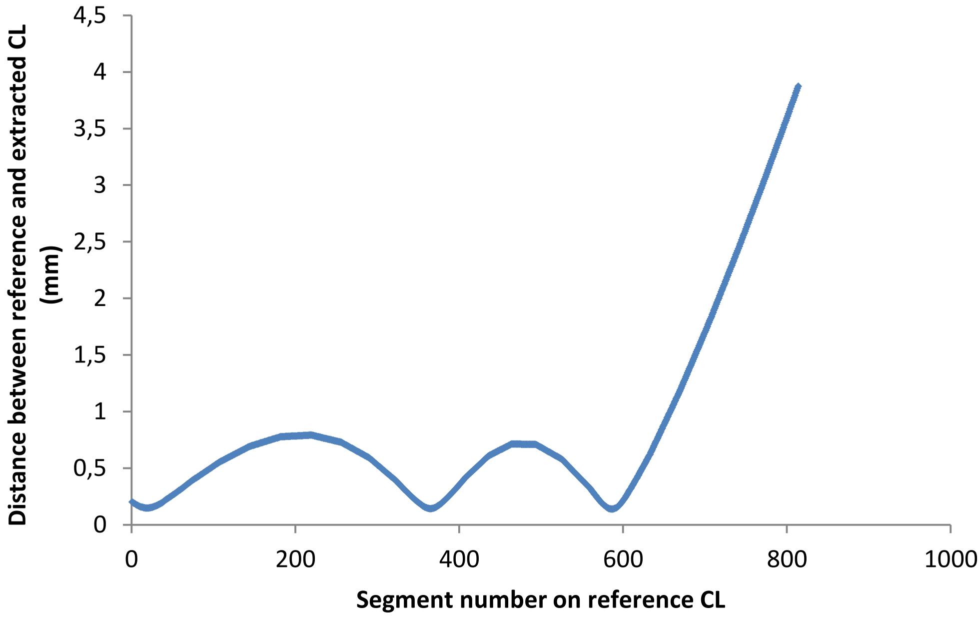

Figure 4: The distance between the reference centerline and the extracted centerline per segment created in the method described above. The high peak for high segment numbers indicates the deviation of the extracted centerline from its central position towards the end of the blood vessel.

Table 2: Overview of the median distance between the reference centerline and the extracted centerline, the radius of the model, the relative median distance (ratio of median distance to radius), and the 80th percentile per model for centerlines extracted in Mimics 15.0 under default settings.

	Median distance - Mimics 15.0 default (smooth factor 0.5) [mm]	*Radius [mm]*	*Relative median distance to the reference centerline in %*	*80th percentile [mm]*
Tube	0.63	20	3.15	0.91
Sine tube	0.19	5	3.80	0.27
Sausage	0.10	30 (largest) 17.7 (smallest)	0.33 0.57	0.16
Helix	0.41	7.5	5.47	0.68
Tree	See separate table below	4.5	See separate table below	See separate table below

Table 3: Overview of the median distance between the reference centerline and the extracted centerline, the radius of the model, the relative median distance (ratio of median distance to radius), and the 80th percentile per branch of the tree model for the centerline extracted in Mimics 15.0 under default settings.

	Median distance - Mimics 15.0 default (smooth factor 0.5) [mm]	Radius [mm]	Relative median distance to the reference centerline in %	80th percentile [mm]
Tree branch segment 1	0.15	4.5	3.33	0.24
Tree branch segment 2	0.20	4.5	4.44	0.29
Tree branch segment 3	0.30	4.5	6.67	0.80
Tree branch segment 4	0.62	4.5	13.78	1.68
Tree branch segment 5	0.28	4.5	6.22	0.46
Tree branch segment 6	0.35	4.5	7.78	0.48
Tree branch segment 7	0.16	4.5	3.56	0.25
Tree branch segment 8	0.15	4.5	3.33	0.17
Tree branch segment 9	0.18	4.5	4.00	0.24
Tree branch segment 10	0.31	4.5	6.89	0.65
Tree branch segment 11	0.30	4.5	6.67	0.36
Tree branch segment 12	0.42	4.5	9.33	0.56
Tree branch segment 13	0.34	4.5	7.56	0.49
Tree branch segment 14	0.24	4.5	5.33	0.47
Tree branch segment 15	0.24	4.5	5.33	0.39
Tree branch segment 16	0.19	4.5	4.22	0.35
Tree branch segment 17	0.18	4.5	4.00	0.29
Tree branch segment 18	0.17	4.5	3.78	0.29
Tree branch segment 19	0.42	4.5	9.33	0.56
Tree branch segment 20	0.36	4.5	8.00	0.66

The median deviation of the default extracted centerline to the reference centerline is largest in the Tube model. Narrowing doesn't seem to effect the centerline's position strongly as the deviation in the sausage model is very low. The deviation in the Helix model, combining curvature and tortuosity, is still smaller than the most basic Tube model. This results from the fact that the centerline algorithm automatically calculates the two parameters described above for extracting the central control points, namely the 'resolving resolution' and the 'control points distance'. The extraction in a model with a smaller diameter, and with more detail will be done with a smaller resolving resolution, and a smaller control points distance, leading to a higher degree of centricity in this case.

While comparing the centricity deviation from the extracted centerline with the radius of the model, it is shown that the centerline relatively doesn't deviate much from the true blood vessel center. Only 5.5 % relative median distance is found in the most complex model, namely the Helix model combining curvature and tortuosity.

In the tree model however, some branches have higher relative median distances. This is due to the large deviations of the extracted centerline from the reference centerline around the branching points, and at the endings of the branches. Especially, the small branches lead to high distance values. At both sides of the branch, there is a large deviation, biasing the median and the 80th percentile. The branching point of a blood vessel branch is a concept which doesn't exist physically. Therefore, the branching point is not uniquely defined. Its place depends on the interpretation of the user. At any time, the user can update the branching point location via the 'Edit Centerline Control points' tool.

The branching points detection was changed between Mimics 15.0 and 16.0. The following table gives a comparison between, on the one hand, the deviation of the centerline extracted in Mimics 15.0 with default settings from the reference centerline, and, on the other hand, the deviation of the centerline extracted in Mimics 16.0 with default settings from the reference centerline (Table 4).

Table 4: Overview of the median distance between the reference centerline and the extracted centerline, and the 80th percentile per branch of the tree model, both for the centerline extracted in Mimics 15.0, and in Mimics 16.0.

	Median distance - Mimics 15.0 default (smooth factor 0.5) [mm]	*80th percentile [mm]*	*Median distance – Mimics 16.0 default (smooth factor 0.5) [mm]*	*80th percentile [mm]*
Tree branch segment 1	0.15	0.24	0.35	0.69
Tree branch segment 2	0.20	0.29	0.45	0.76
Tree branch segment 3	0.30	0.80	0.19	0.29
Tree branch segment 4	0.62	1.68	0.44	0.95
Tree branch segment 5	0.28	0.46	0.19	0.33
Tree branch segment 6	0.35	0.48	0.18	0.31
Tree branch segment 7	0.16	0.25	0.18	0.36
Tree branch segment 8	0.15	0.17	0.16	0.32
Tree branch segment 9	0.18	0.24	0.26	0.47
Tree branch segment 10	0.31	0.65	0.26	0.42
Tree branch segment 11	0.30	0.36	0.26	0.52
Tree branch segment 12	0.42	0.56	0.14	0.34
Tree branch segment 13	0.34	0.49	0.26	0.37
Tree branch segment 14	0.24	0.47	0.33	0.61
Tree branch segment 15	0.24	0.39	0.17	0.23
Tree branch segment 16	0.19	0.35	0.18	0.23
Tree branch segment 17	0.18	0.29	0.62	0.98
Tree branch segment 18	0.17	0.29	0.32	0.51
Tree branch segment 19	0.42	0.56	0.31	0.53
Tree branch segment 20	0.36	0.66	0.38	0.42
Average over all branch segments	0.28	0.48	0.28	0.48

As can be seen from the averages over all branch segments, the overall result from the branching point detection in Mimics 15.0 and 16 is not different (Table 4 and Figure 5). Nevertheless, the algorithm used in Mimics 16.0 is deterministic. Therefore, the same results can be expected in all cases.

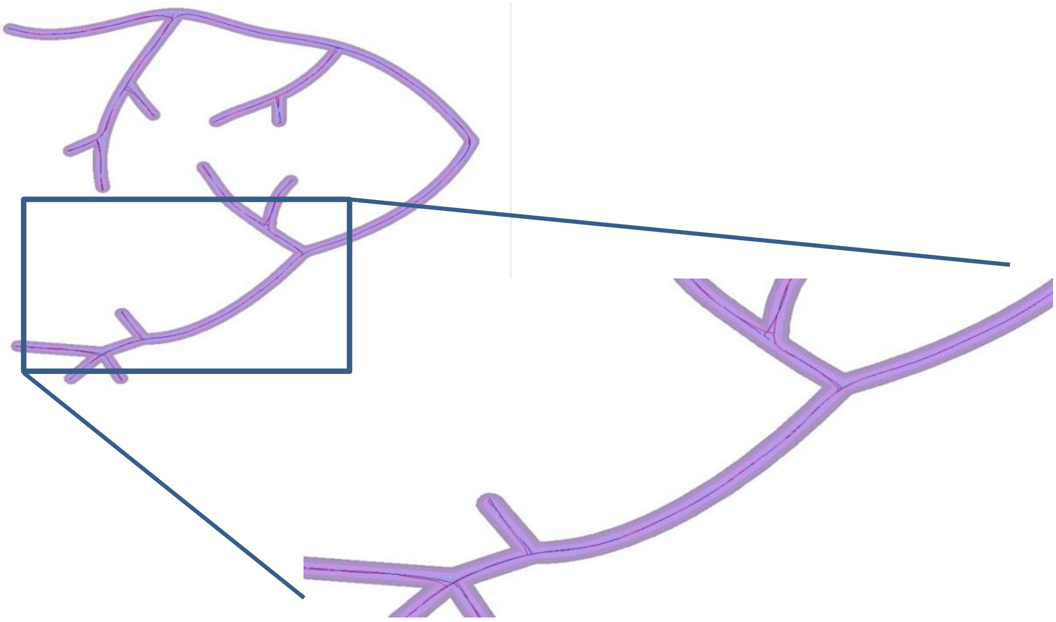

Figure 5: The tree model without noise, with the reference centerline in cyan, the centerline extracted in Mimics 15.0 with default settings in red, and the centerline extracted in Mimics 16.0 with default settings in purple.

The deviation in all cases remains very low, and tolerable for different applications. Except in the tube model, and in some branch segments of the tree, the median deviation is lower than 0.6 mm, the most common resolution of current cardiovascular scans. The 80th percentile lies for all models below 1 mm, meaning that 80 % of all values are below 1 mm (except for branch segment 4 of the Tree model in Mimics 15.0).

2.2. Differences between the model with noise SD20

To evaluate the effect of curvature, tortuosity, changing diameter, and branching on the centerline extraction under normal levels of noise, the deviation of the default extracted centerline to the reference centerline is compared between the different models with noise SD = 20 (Table 5).

Table 5: Overview of the median distance between the reference centerline and the extracted centerline, the radius of the model, the relative median distance (ratio of median distance to radius), and the 80th percentile per model with normal levels of noise (SD = 20) for centerlines extracted in Mimics 15.0 under default settings.

	Median distance - Mimics 15.0 default (smooth factor 0.5) [mm]	*Radius [mm]*	*Median distance to the reference centerline in %*	*80th percentile [mm]*
Tube	/	20	/	/
Sine tube	0.09	5	4.60	0.11
Sausage	/	30 (largest) 17.7 (smallest)	/ /	/
Helix	0.38	7.5	5.07	0.66
Tree (average over branch segments)	0.29	4.5	6.44	0.52

When normal levels of noise are present, the algorithm with default settings is not able to extract a correct centerline in the Tube, and the sausage model. The noise results in a centerline with incorrect side branches. In these cases, the noise is interpreted as small blood vessels by the algorithm.

There are two possible solutions for this problem:

1) Smooth the 3D model before extracting the centerline (Figure6)
2) Set the centerline parameters manually (Figure 6): for example put the resolving resolution at 5 mm to decrease the detail detected.

In Mimics 15.01, and Mimics 16.0, the algorithm is improved concerning the branching points calculation, and these types of branches are automatically deleted (Figure 6).

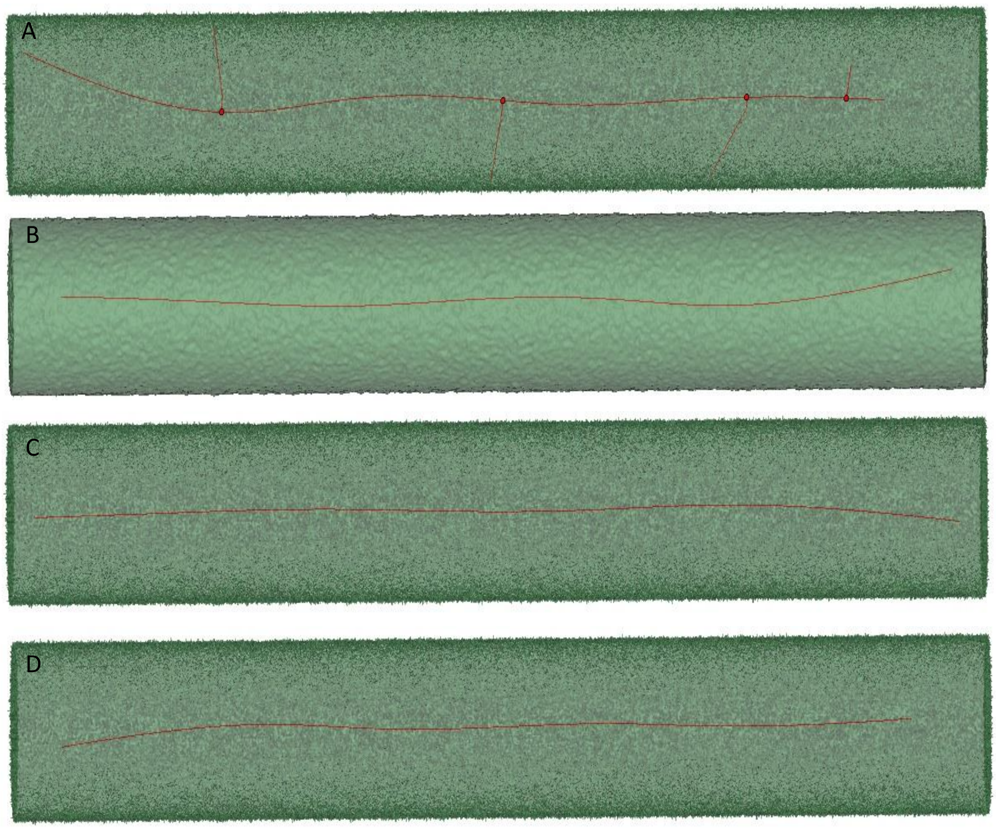

Figure 6: Tube model with noise SD20 with several extracted centerlines. A: default centerline extracted in Mimics 15.0, B: smoothed Tube model with noise SD20 with default centerline extracted in Mimics 15.0, C: centerline extracted in Mimics 15.0 after setting the resolving resolution fixed to 5 mm (smooth factor is kept on default value of 0.5), D: default centerline extracted in Mimics 16.0.

The median distances are all smaller than 0.6 mm, the most common resolution of current cardiovascular scans. All 80th percentile values are below 1 mm (Table 5).

2.3. Differences between the models without noise and with noise (centerline extraction in Mimics 15.0 with default settings)

To evaluate the effect of noise on the deviation of the default extracted centerline to the reference centerline, the centerline extractions in the different models with different levels of noise are compared to each other (Table 6).

Table 6: Overview of the median distance between the reference centerline and the extracted centerline, and the relative median distance (ratio of median distance to radius) per model, and per noise level (no noise, SD = 20, SD = 40, SD = 80) for centerlines extracted in Mimics 15.0 under default settings.

	Without noise		*With noise SD20*		*With noise SD40*		*With noise SD80*	
	Median distance	Relative median distance	Median distance	Relative median distance	Median distance	Relative median distance	Median distance	Relative median distance
Tube	0.63	0.0315	/	/	/	/	/	/
Sine tube	0.19	0.0380	0.23	0.0460	0.20	0.0400	0.22	0.0440
Sausage	0.10	0.0033 (largest diameter) 0.0056 (smallest diameter)	/	/ /	/	/ /	/	/ /
Helix	0.41	0.0547	0.39	0.0507	0.46	0.0613	0.44	0.0587
Tree (average over branch segments)	0.28	0.0622	0.29	0.0644	0.31	0.0689	0.33	0.0733

The effect of noise seems to be very low. Moreover, the difference between the effects of several levels of noise seems to be random. This could be explained by the fact that the algorithm calculates the resolving resolution, and control points distance automatically based on the input. Depending on the position of the noise peaks, slightly different resolving resolution, and control points distances will be calculated. As those noise peaks are random, the results vary without a clear trend from low to high noise levels.

The median distances are all smaller than 0.6 mm, the most common resolution of current cardiovascular scans. Nevertheless, as described above, in Mimics 15.0, noise can cause false branches on the centerline, a problem which is solved in Mimics 15.0.1 and 16.

2.4. Differences between the centerline extractions with no smoothing and with smoothing (models with noise SD20, CL extracted in Mimics 15.0 with smooth factor = 0, and default smooth factor = 0.5)

To evaluate the effect of smoothing on the deviation of the default extracted centerline to the reference centerline, the (relative) median distances and the 80th percentile are compared between centerline extractions with default smoothing (smooth factor = 0.5) and with no smoothing for all models with normal levels of noise (noise with SD = 20) (Table 7).

Table 7: Overview of the median distance between the reference centerline and the extracted centerline, the relative median distance (ratio of median distance to radius), and the 80th percentile per model with noise level SD =20 for centerlines extracted with the default smoothing level (smooth factor = 0.5), and with no smoothing (smooth factor = 0).

	Mimics 15.0 default smooth factor=0.5			*Mimics 15.0 smooth factor=0*		
	Median distance [mm]	Relative median distance	80th percentile [mm]	Median distance [mm]	Relative median distance	80th percentile [mm]
Tube with noise SD 20	/	/	/	/	/	/
Sine tube with noise SD 20	0.09	0.0192	0.11	0.05	0.0100	0.08
Sausage with noise SD 20	/	/	/	/	/	/
Helix with noise SD 20	0.39	0.0507	0.66	0.39	0.0520	0.46

Tree with noise SD 20 (average over branch segments)	0.29	0.0644	0.52	0.13	0.0289	0.23

There is always a trade-off between smoothness and centricity of the centerline. Due to the smoothing process, the centerline might deviate from its central position.

In the table above, in the presence of normal levels of noise, smoothing can have almost no effect or a negative effect on centricity of the centerline, depending on the model. In general, the differences between smoothing and no smoothing are very low, and all median distances are smaller than 0.6 mm, the most common resolution of current cardiovascular scans. The user can influence the level of smoothing via the smooth factor parameter as described above.

2.5. Differences between the centerline extractions with no smoothing and with smoothing (models with noise SD40, CL extracted in Mimics 15.0 with smooth factor = 0, and default smooth factor = 0.5)

To evaluate the effect of smoothing on the deviation of the default extracted centerline to the reference centerline, the (relative) median distances and the 80th percentile are compared between centerline extractions with default smoothing (smooth factor = 0.5) and with no smoothing for all models with high levels of noise (noise with SD = 40) (Table 8).

Table 8: Overview of the median distance between the reference centerline and the extracted centerline, the relative median distance (ratio of median distance to radius), and the 80th percentile per model with noise level SD =40 for centerlines extracted with the default smoothing level (smooth factor = 0.5), and with no smoothing (smooth factor = 0).

	Mimics 15.0 default smooth factor=0.5			*Mimics 15.0 smooth factor=0*		
	Median distance [mm]	Relative median distance	80th percentile [mm]	Median distance [mm]	Relative median distance	80th percentile [mm]
Tube with noise SD 40	/	/	/	/	/	/
Sine tube with noise SD 40	0.20	0.0400	0.25	0.15	0.0300	0.19
Sausage with noise SD 40	/	/	/	/	/	/
Helix with noise SD 40	0.46	0.0613	0.83	0.46	0.0613	0.61
Tree with noise SD 40 (average over branch segments)	0.31	0.0689	0.60	0.19	0.0422	0.41

In the presence of higher levels of noise, typical for ultrasound images, the same behavior can be seen as in the presence of normal levels of noise for CT or MRI (see above).

2.6. Differences between the centerline extractions with no smoothing and with smoothing (models with noise SD80, CL extracted in Mimics 15.0 with smooth factor = 0, and default smooth factor = 0.5)

To evaluate the effect of smoothing on the deviation of the default extracted centerline to the reference centerline, the (relative) median distances and the 80th percentile are compared between centerline extractions with default smoothing (smooth factor = 0.5) and with no smoothing for all models with very high levels of noise (noise with SD = 80) (Table 9).

Table 9: Overview of the median distance between the reference centerline and the extracted centerline, the relative median distance (ratio of median distance to radius), and the 80th percentile per model with noise level SD =80 for centerlines extracted with the default smoothing level (smooth factor = 0.5), and with no smoothing (smooth factor = 0).

	Mimics 15.0 default smooth factor=0.5			*Mimics 15.0 smooth factor=0*		
	Median distance [mm]	Relative median distance	80th percentile [mm]	Median distance [mm]	Relative median distance	80th percentile [mm]
Tube with noise SD 80	/	/	/	/	/	/
Sine tube with noise SD 80	0.22	0.0440	0.31	0.18	0.0360	0.23
Sausage with noise SD 80	/	/	/	/	/	/
Helix with noise SD 80	0.44	0.0587	0.71	0.42	0.0560	0.59
Tree with noise SD 80 (average over branch segments)	0.33	0.0733	0.50	0.22	0.0489	0.37

The presence of very high levels of noise doesn't change the conclusions observed in cases with lower levels of noise (see above).

2.7. Differences between the centerline extractions from Mimics 15.0 and Mimics 17.0 in the Helix model with smoothing (models with noise SD20, CL extracted in Mimics 15.0 and in Mimics 17.0 with default smooth factor = 0)

In Mimics 17.0, the centerline extraction algorithm is changed by implementing a cubic spline interpolation instead of a quadratic spline interpolation. It is still possible to use the quadratic interpolation to compare results in Mimics 17.0 with results obtained in a previous Mimics version. Nevertheless, the default in Mimics 17.0 is cubic interpolation. By using this type of interpolation, the curvature will become a smooth, continuous measurement without losing the centricity of the centerline. This is most apparent in coronary blood vessels, where the Mimics 15.0 and 16.0 centerline extraction algorithm resulted in non-continuous curvature measurements (Figure 7).

To evaluate the effect of cubic spline interpolation versus quadratic spline interpolation on the centricity of the centerline, the (relative) median distances and the 80th percentile are compared between centerline extractions with default settings (smooth factor = 0.5) (Table 10) and no smoothing (smooth factor = 0) (Table 11) in Mimics 15.0 and in Mimics 17.0, and the reference centerline for the Sine Tube model with noise SD = 20, the Helix model with noise SD = 20.

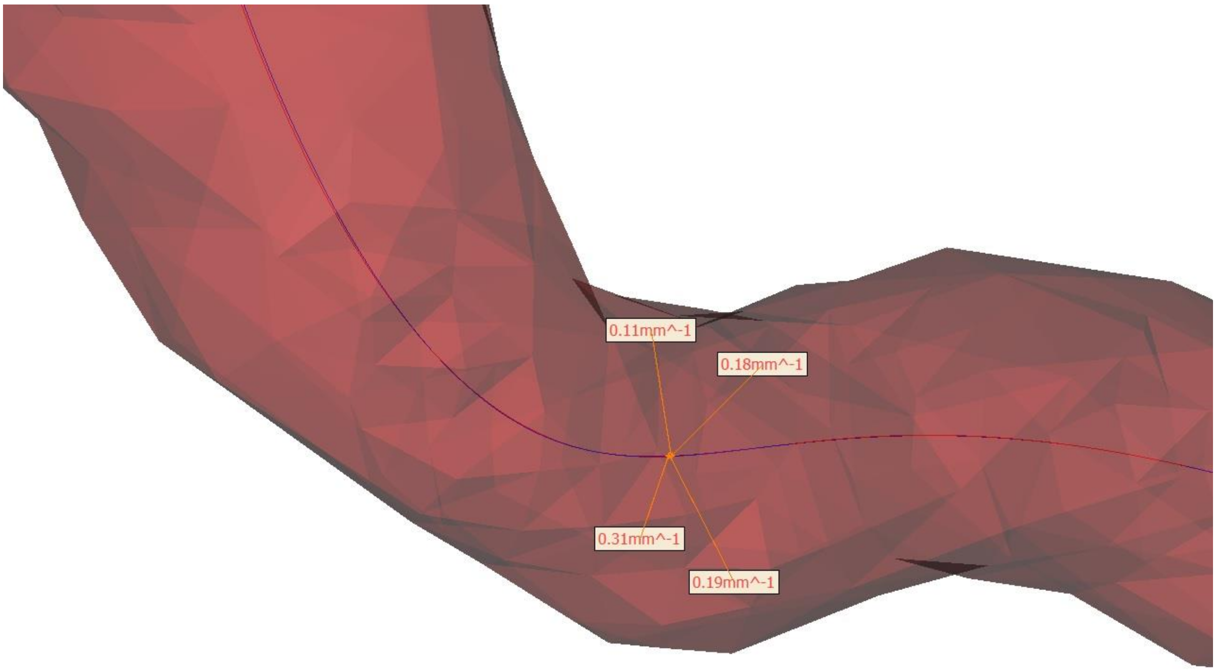

Figure 7: 3D model of a coronary vessel with a centerline extracted in Mimics 15.0 (red) (quadratic spline interpolation), and a centerline extracted in Mimics 17.0 (blue) (cubic spline interpolation). Curvature measurements in two adjacent points on the Mimics 15.0 (and 16) centerline are shown left, and the ones on the Mimics 17.0 centerline are shown on the right.

Table 10: Overview of the median distance between the reference centerline and the extracted centerline, the relative median distance (ratio of median distance to radius), and the 80th percentile in the helix model with noise level SD = 20 for centerlines extracted with the default smoothing level (smooth factor = 0.5) in Mimics 15.0 and in Mimics 17.0.

	Mimics 15.0 default smooth factor=0.5			*Mimics 17.0 default smooth factor=0.5*		
	Median distance [mm]	Relative median distance	80th percentile [mm]	Median distance [mm]	Relative median distance	80th percentile [mm]
Sine Tube with noise SD 20	0.09	0.0192	0.11	0.18	0.0353	0.28
Helix with noise SD 20	0.39	0.0507	0.66	0.51	0.0681	0.80

Table 11: Overview of the median distance between the reference centerline and the extracted centerline, the relative median distance (ratio of median distance to radius), and the 80th percentile in the helix model with noise level SD = 20 for centerlines extracted with no smoothing (smooth factor = 0) in Mimics 15.0 and in Mimics 17.0.

	Mimics 15.0 smooth factor=0			*Mimics 17.0 smooth factor=0*		
	Median distance [mm]	Relative median distance	80th percentile [mm]	Median distance [mm]	Relative median distance	80th percentile [mm]
Sine Tube with noise SD 20	0.05	0.0100	0.08	0.09	0.0173	0.12
Helix with noise SD 20	0.39	0.0520	0.46	0.47	0.0624	0.61

There is a trade-off between centerline centricity and smooth curvature. By using a cubic spline interpolation instead of a quadratic spline interpolation, the curvature is continuous by definition but centricity of the centerline is lower. Nevertheless, the distances between the centerline extracted in Mimics 17.0 compared to the reference centerline are only slightly higher compared to the distances between the centerline extracted in Mimics 15.0 and the reference centerline.

General discussion

A few general issues need further discussion. More explanation is given below.

1. Tolerance

The distance between the reference centerline and the extracted centerline should be below the pixel size. Nowadays, CT scans with a resolution of 0.6 mm/pixel are common in cardiovascular applications. With dual source scanners, even a resolution of 0.3 mm/pixel can be reached.

A less strict tolerance for the distance between the reference centerline and the extracted centerline could be the differences in stent sizes now available on the market. The Corevalve for example comes in sizes 26 mm, 29 mm, and 31 mm. To be able to choose between these sizes, a maximal error of 1 mm in the centerline deviation could be tolerated.

2. Endings and branching points problem

The largest deviations between the reference and the extracted centerline are situated around the endings and around the branching points.

2.1. Endings problem

At the endings of model, both centerlines, the reference one and the extracted one, deviate highly from each other due to the following issues:

- At endings, the extraction of the centerline algorithm is attracted to the edge of the model.
- The extracted and reference centerline have different lengths. For the comparison, they are divided in parts of equal length. Therefore, some segments deviate highly from each other at the endings of a model.

2.2. Branching points problem

At the branching points, both centerlines, the reference one and the extracted one, can deviate highly from each other due to the following issue:

- The branching point of a blood vessel branch is a concept which doesn’t exist physically. Therefore, the branching point is not uniquely defined. Its place depends on the interpretation of the user. In Mimics, a choice was made to define the branching point. However, if the user is not pleased with the branching point’s place, it can be changed via the ‘Edit Centerline Control Points’ tool.

3. Smoothing & curvature

The users of Mimics 14 encountered a problem with curvature measurements on the centerline. Due to a non-smooth centerline, measured curvature values were higher than the actual anatomy curvature (Figure 8). Therefore, in Mimics 15.0, a new smoothing algorithm was introduced, namely Fourier smoothing. This leads to normal curvature values, as can be appreciated in the figure below (Figure 8).

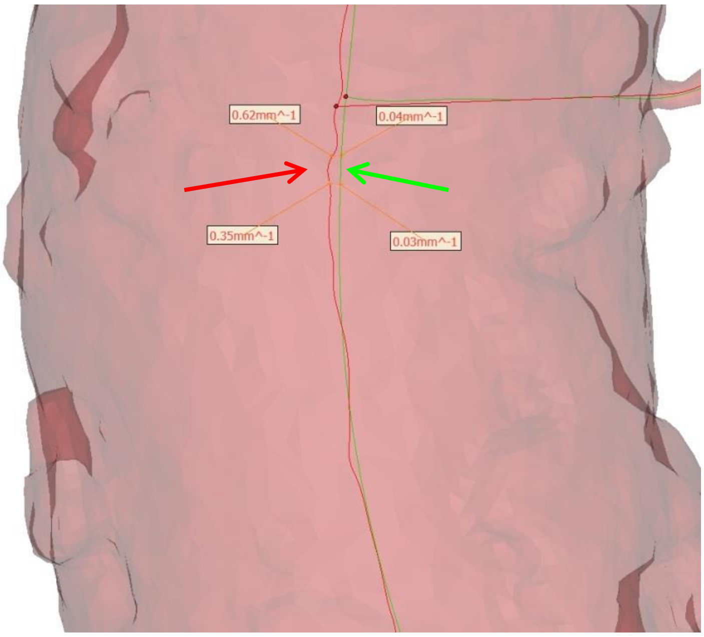

Figure 8: The 3D model of an aorta with a centerline extracted in Mimics 14 (red centerline), and a centerline extracted in Mimics 15.0 (green centerline). The difference in smoothing, and its effect on curvature values, is indicated by the red and green arrow.

Nevertheless, in Mimics 15.0 and 16, in some cases, discontinuous curvature values over a continuous centerline can be found. This results from the fact that curvature calculation is based on the spline visualization of the centerline. In Mimics 15.0 and 16, a quadratic spline is used. In Mimics 17.0, by default, a cubic spline is used (Figure 7). To compare results obtained in previous versions of Mimics, the spline can be changed from cubic to quadratic in the centerline properties dialog.

Conclusions

In conclusion, the centerline extracted in Mimics lies in the center of the blood vessel, with a possible median deviation typically below one pixel of 0.6 mm, the common resolution for cardiovascular scans. In some cases, the deviation can be larger. In general, it can be said that the centerline will lie within a tolerance of 2 pixels (under scan resolution of 0.6 mm) in the center of the blood vessel.

Only towards the endings of the blood vessels, the centerline extraction algorithm cannot find the center of the blood vessel. To solve this problem, the user can use the ‘Cut Centerline Endings’ tool in Mimics. Because of this deviation towards the endings of the blood vessels, the (1) median distance between the extracted and the reference centerline, and the (2) 80th percentile was checked in the synthetic models. Both measures indicate the centricity of the centerline in the largest portion of the blood vessel with exception of the endings. Smoothing only affects the centricity slightly while highly increasing the smoothness of the centerline. Compared to the centerlines diameter, the centerline deviation from its central position is always below 7.3 %.
In addition, around the branching points, the centerline may deviate from the position it should have according to the interpretation of the user. This is due to the fact that a branching point, is not a physical existing point, and several solutions are possible.

At any time, the user can change the results from the automatic centerline extraction. There are three parameters which can be set manually to influence the results as described above: the resolving resolution, the control points distance, and the smooth factor. Moreover, after the extraction of the centerline, the user can still edit single control points via the ‘Edit Centerline Control Points’ tool. This might be necessary in special zones such as the heart valve. To obtain a better view on this valve, the user can use the ‘Reslice along plane’ >‘Interactive MPR’, or the ‘Reslice along curve’ > ‘Select curve’ tool to reslice the images. In the resulting resliced views, it is possible to use the ‘Edit Centerline Control Points’ tool to precisely move a single control point.

In Mimics 15.01, and Mimics 16.0 an improvement in branching point detection was implemented compared to Mimics 15.0. As a result, the problem of the false branches found in some synthetic models with noise levels, is solved in Mimics 16.0.

In Mimics 17.0, a further improvement is introduced by visualizing the centerline with a cubic spline interpolation by default. This will lead to continuous curvature and triad measurements. However, it is still possible to use a quadratic spline interpolation. In such a way, the user can always compare results obtained in Mimics 17.0 with the ones obtained in Mimics 16.0.

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