A Pilot Study of Video-motion Analysis in Endovascular Surgery: Development of Real-time Discriminatory Skill Metrics[☆]

A.E. Rolls [a,*], **C.V. Riga** [a,b], **C.D. Bicknell** [a,b], **D.V. Stoyanov** [c], **C.V. Shah** [a], **I. Van Herzeele** [a,e], **M. Hamady** [d], **N.J. Cheshire** [a,b]

[a] Division of Surgery, Department of Surgery and Cancer, Imperial College London, UK
[b] Imperial Vascular Unit, Imperial College Healthcare NHS Trust, UK
[c] Hamlyn Centre for Robotic Surgery, Imperial College London, UK
[d] Department of Interventional Radiology, Imperial College Healthcare NHS Trust, UK
[e] Department of Thoracic and Vascular Surgery, Ghent University Hospital, Ghent, Belgium

WHAT THIS PAPER ADDS

In an era of rapid advancement both in endovascular technique and technology, truly objective assessment of competence for the purpose of maintaining the highest standards in vascular care has become essential. Existing methods of assessment involve simulator-based metrics as well as qualitative scoring systems in the live-case setting. The latter often require time-consuming expert-assessments. This study is, to the author's knowledge, the first to describe semi-automated motion tracking of endovascular tools, using video fluoroscopy sequences as a medium for assessment of skill.

Objectives: Accurate assessment and credentialing of physicians is essential.
Objective motion analysis of guide-wire/catheter manipulation to assess proficiency during endovascular interventions remains unexplored. This study aims to assess its feasibility and its role in evaluation of technical ability.

Materials and methods: A semi-automated catheter-tracking software was developed which allows for frame-by-frame motion analysis of fluoroscopic videos and calculation 2D catheter tip path-length. 21 interventionalists (6 cardiologists, 8 interventional radiologists, 7 vascular surgeons; 14/21 had performed >500 endovascular procedures) performed an identical carotid artery stenting procedure (CAS) on a VIST simulator (Mentice, Gothenburg, Sweden). Operators were sub-divided into four categories according to CAS experience: 6 inexperienced (0 CAS-group A), 3 low-volume (1—20 CAS-group B), 5 moderate-volume (21—50 CAS-group C) and 7 high-volume (>50 CAS-group D) CAS experience. Total PL was calculated for each case and comparisons made between groups. PL was correlated with: quantitative, simulator-derived metrics and qualitative performance scores (generic and procedure-specific) derived from post-hoc video analysis by three blinded observers.

Results: Group D used 5160.3 (inter-quartile range- IQR 4046.4—7142.9) pixels of movement, compared to 6856.7 (5914.4—8106.9) for group A ($p = 0.046$); 10,905.1 (7851.1—14,381.5) for group B ($p = 0.017$); and 9482.6 (8663.5—13,847.6) for group C ($p = 0.003$). Statistically significant inverse correlations were seen between total PL and qualitative performance scores (rho $= -0.519$ for generic ($p = 0.027$) rho $= -0.567$ for procedure-specific ($p = 0.014$) scores). PL did not correlate with any of the simulator-derived metrics (errors, contrast volume, total procedure and fluoroscopy times, cine-loops used).

Conclusion: Endovascular instrument video motion analysis is feasible and may represent a valuable tool for the objective assessment of endovascular skill.

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[☆] The data in this paper has also been reported in part in a previous paper using the same cohort of participants (Van Herzeele et al., J Vasc Surg 2007;46:855—63). The originality of this article lies with the presentation of a novel method of endovascular skill assessment.

[*] Corresponding author. A.E. Rolls, 10th Floor Academic Surgical Unit, QEQM Building, St. Mary's Hospital, Praed Street, London W2 1NY, UK. Tel.: +44 (0) 7719868304 (mobile).

E-mail address: alex.rolls1981@googlemail.com (A.E. Rolls).

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INTRODUCTION

In an era of reduced working hours and increased patient demands it has become necessary not only to offer additional training opportunities outside the remit of the traditional surgical apprenticeship model, but also to provide a means by which surgical performance can be assessed. Simulation offers the opportunity to train in an educationally-oriented environment without subjecting patients to increased risk, whilst also providing the opportunity for on-going feedback and assessment outside the demands of clinical case workload. Most high-fidelity simulators, such as the VIST (Mentice, Gothenburg, Sweden), provide instantaneous and automated feedback on metrics such as total procedure and fluoroscopy times and simulator-recorded errors. The metrics recorded by a variety of simulators have demonstrated good construct validity in terms of endovascular training and experience.[1–3] However, such metrics can only be regarded as crude surrogate markers of technical skill and the overall quality of endovascular performance. Several qualitative rating scales have been developed in an attempt to assess endovascular performance, for example the generic endovascular rating scale[4] and the procedure-specific rating scale.[2] Many of these are derived from the generic Objective Structured Assessment of Technical Skills (OSATS)[5] and incorporate domains such as knowledge and handling of endovascular material, pre-planning, clinical decision making, as well as technical aspects such as catheter/wire manipulation skills. Whilst many of these qualitative scoring systems demonstrate construct validity and good inter-observer reliability, they require time-consuming, video-based post-hoc analyses by at least two experts. In addition, assigning numerical values to qualitative statements exposes these assessments to a degree of subjectivity.

Motion analysis as a tool to evaluate skill is currently unexplored in the field of endovascular surgery. The technology does exist to track hand movements during open and laparoscopic surgery.[6] We hypothesise that surgical efficiency can be measured by tracking the distal-most tip of the surgical instrument, and in the case endovascular intervention; the tip of the guide-wire or catheter. A reduction of total movement (or path-length) required to successfully complete an endovascular task, may represent a reliable measure of skill. The primary objective of this study was therefore to study a novel endovascular metric — guide-wire/catheter tip path-length (PL), in order to determine whether this constitutes an objective and sensitive discriminator of endovascular skill. The secondary objective was to correlate PL with existing simulator-derived metrics and qualitative rating scales.

METHOD

Subjects

Twenty-one endovascular physicians participated in this study. Each had performed at least 100 general endovascular cases as primary operator. This number was arbitrarily selected to realistically reflect the minimum endovascular experience required for carotid artery stenting (CAS) training. Six interventional cardiologists (IC), eight interventional radiologists (IR) and seven vascular surgeons (VS) participated. 66% had performed at least 500 endovascular interventions as primary operator. They were sub-divided into four categories according to CAS experience: inexperienced (0 CAS cases performed, 3 IR and 3 IC participants), low-volume (1—20 CAS cases performed, 2 VS and 1 IC participants), moderate-volume (21—50 CAS cases performed, 1 VS, 2 IR and 2 IC participants) and high-volume interventionalists ($>$50 CAS cases performed, 4 VS and 3 IR participants). The moderate- and high-volume groups had performed only 1 and 2 previous virtual-reality simulations, respectively. No one in the inexperienced or low-volume groups had previous VIST experience.

The vascular intervention simulation trainer (VIST) simulator

The VIST simulator is a high fidelity endovascular simulator which consists of a personal computer-based software interface (Procedicus, Mentice AB, Gothenburg, Sweden) and two monitors linked to an interface device that allow the user to insert and manipulate wires, catheters, balloons, stents and other endovascular tools. The subject begins the procedure by selecting specific tools that are inserted into the user interface, which represents the virtual patient. A fluoroscopic image activated by a foot pedal is displayed together with the virtual tools. Separate controllers for simulated stent deployment, balloon inflation, and contrast material injection are provided. User interface functions include fluoroscopic C-arm positioning, table movements, road mapping and cine-loop recording.

Task performed

All subjects received an initial didactic session on the VIST simulator and were familiarised with the system followed by a practice session of treating an ipsilateral common iliac artery stenosis. Prior to study commencement, available endovascular materials and patient's records demonstrating the target lesion were provided. All participants were asked to treat a proximal right internal carotid artery stenosis (90%) endovascularly in a type 1 aortic arch. The purpose of this study was to validate metrics for endovascular skill assessment rather than knowledge, so for less experienced subjects in CAS a protocol was available explaining the different steps of the CAS procedure. Passive assistance was provided by members of the interventional team comprising of an assistant, radiographer, and a circulating nurse.

Catheter tracking software

A software package was created in C++ and using the OpenCV library (http://opencv.willowgarage.com/) to allow video file editing and frame-accurate analysis of fluoroscopic video sequences. A semi-automatic scheme was used to track the motion of the catheter and guide-wire tip

Figure 1. Animations of known length used to assess inter-observer reliability.

during the simulated procedure. The user selects the tip of the endovascular tool in an initial video frame using the mouse cursor and the software then estimates the tip's position in subsequent video frames. The software generates pixel co-ordinates based on the catheter tip's position on a frame-by-frame basis from which distance in 2D (path-length) data are obtained.

The initial tracking point was standardised and defined as the origin of the left subclavian artery. In all procedures the most distal part of the guide-wire/catheter interface was tracked (either the guide-wire or catheter tip). Estimation of each tracker position was performed using a search template to match the position in subsequent frames.

Pre-processing of video frames was performed for correction of perspective distortion due to the positioning of the recording camera with respect to the simulator's monitor. The correction was based on the user selecting the four corners of the simulator screen in any given video dataset. This allowed a transformation of pixel co-ordinates to be computed to adjust the data to the observed screen co-ordinates thus removing any dependence on the recording camera's position and viewing orientation. The dataset of pixel co-ordinates for each individual video can then be fairly compared to other datasets because intra-variability of co-ordinates has been removed.

In order to assess inter-observer variability/reproducibility the video-motion analysis software was applied to animations of known trace-lengths in order to calculate PL. Each animation was tracked by five different operators (Fig. 1). Cronbach's α was used to test for inter-observer variability.

Data analysis

Post-hoc video analysis of all procedures was performed by a blinded assessor using the catheter tracking software described above. Phases of active movement were tracked, and tracking was not performed during phases of angiographic image manipulation (such as C-arm rotation) in order to avoid incorporation of movement artefact into the final PL analysis.

Each case was segmented into four defined procedural phases. Arch Navigation was defined as movement from the left subclavian ostium to a resting position of guide-wire and catheter at the aortic root. Right common carotid artery cannulation (CCA) was defined as movement from the aortic root to a point 1 cm distal to the right CCA ostium. External carotid artery (ECA) manipulation was defined as movement from 1 cm within the CCA to a position 2 cm within the ECA. Internal carotid artery (ICA) manipulation was defined as movement from within the CCA, across the ICA stenosis to a point at the distal most bend of the ICA. For each subject the wire/catheter tip PL was calculated for the entire procedure as well as the four different procedure phases. The output measure is given in number of pixels.

The VR simulator records instantly and automatically the procedure time, fluoroscopy time, contrast volume used, number of cine-loops used and simulator-defined errors. Errors are classified into catheter vessel errors (pressing catheters against the vessel wall), catheter movement errors (moving catheters without support of a guide wire), moving near a lesion (wire and catheter), moving the embolic protection device (during and after deployment), moving the stent during deployment (and deploying whilst in the guiding catheter or sheath) and inflating the balloon inside the guiding catheter. Qualitative procedural scores were obtained for comparison with PL; three blinded independent experts assessed each procedure using a validated general endovascular rating scale and a CAS-specific rating scale;[2] a median score was calculated. Therefore, each performance was awarded a median CAS- and generic-endovascular rating as a result of the three assessments. As described in previous

Table 1. Table containing path-length data for each phase of the procedure according to groups of experience. *P* values are given following analysis of distributions using Kruskal—Wallis test.

	Group A (0 CAS)	Group B (1—20 CAS)	Group C (21—50 CAS)	Group D {>50 CAS}	[*p*=]
Total PL					
Median	6856.7	10,905.1	9482.6	51,603	0.02
IQR	5914—8107	7851—14,381	8663—13,848	4046—7143	
Arch. Nav.					
Median	1111.7	2178	2841	864.7	0.36
IQR	887—1858	617—5606	1269—4204	764—2106	
CCA					
Median	1358	1790	1063	782	0.83
IQR	959—1587	576—9238	732—1545	648—1849	
ECA					
Median	980	1276	1013	661	0.21
IQR	591—1079	956—1760	670—1310	317—929	
ICA					
Median	245	729	449	297	0.047
IQR	214—292	279—1779	295—826	278—473	AvC: $p = 0.03$

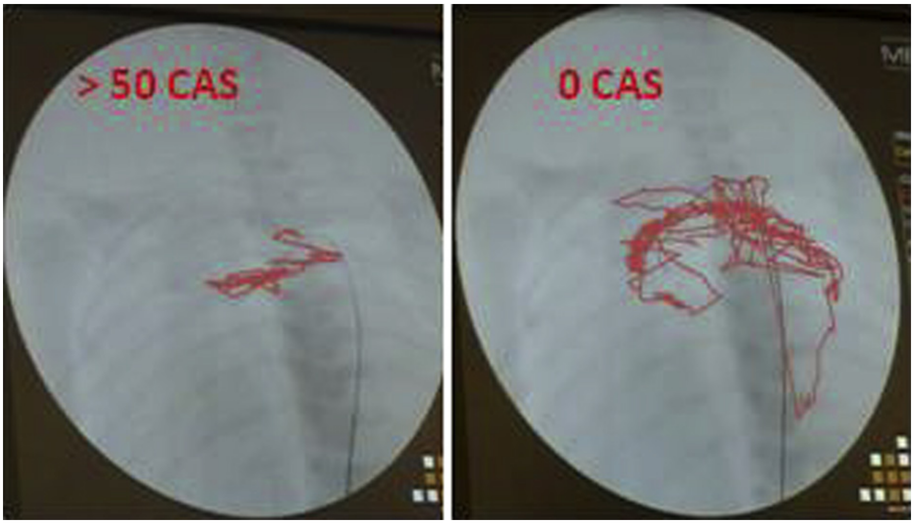

Figure 2. Graphical representation of tracked guide-wire trajectories during arch navigation in simulated carotid artery stenting (CAS). Seen in this format, the greater PL of the inexperienced interventionalist (0 CAS) becomes evident.

publications, the generic-endovascular rating scale was adapted from OSATS and was designed to test various aspects of basic general endovascular skills.[4] Descriptive comments for each of the eight technical domains are given at anchor points for scores 1 (very poor), 3 and 5 (clearly superior). The maximum possible score is 40 (Table 1).

The procedure specific rating scale was designed to assess endovascular skills specifically required to complete CAS safely; it was developed by five endovascular therapists from various medical backgrounds.[2] Seven categories are defined entailing the five key tasks of a CAS procedure, quality of final product and overall performance, each rated on a Likert scale from 1 to 5. The maximum possible score was 35. The higher the score on both scales, the better the performance.

Statistical analysis

Data were analysed with the Statistical Package for Social Sciences 20.0 (SPSS, Chicago, Ill). The data was found to be not normally distributed and therefore non-parametric tests were used. Distributions across all four groups of experience as well as groups according to specialty were compared using the Kruskal—Wallis test. Pre-defined post-hoc comparisons of PL between each group of interventionists with similar CAS experience were performed using the Mann—Whitney *U* test. Correlations between PL and rating scale procedure scores, total procedure time, fluoroscopy time, contrast volume, number of cine-loops and simulator-recorded errors were performed using Spearman's rank correlation coefficient. A level of $p < 0.05$ was considered to be statistically significant.

RESULTS

It was feasible to track path-length of endovascular tools using this semi-automated method with minimal manual adjustment. Typical graphical representations of path lengths can be seen overlain onto the angiographic image in Fig. 2. Testing for inter-observer reliability yielded a Cronbach α of 1.0.

Path-length differences between groups of experience

Analysis of distribution across all four groups using the Kruskal—Wallis test showed statistically significant differences between groups ($p = 0.02$). Except for the group with no prior experience with CAS, there was a decrease in PL with increasing experience. Post-hoc analysis demonstrated the PL was significantly reduced in the highly experienced group D when compared to other groups with CAS experience (Fig. 3). Group D used 5160.3 (interquartile range- IQR 4046.4—7142.9) pixels of movement compared to 6856.7 (5914.4—8106.9) for group A ($p = 0.046$); 10,905.1 (7851.1—14,381.5) for group B ($p = 0.017$) and 9482.6 (8663.5—13,847.6) for group C ($p = 0.003$).

There was no significant difference in PL across groups according to specialty ($p = 0.5$).

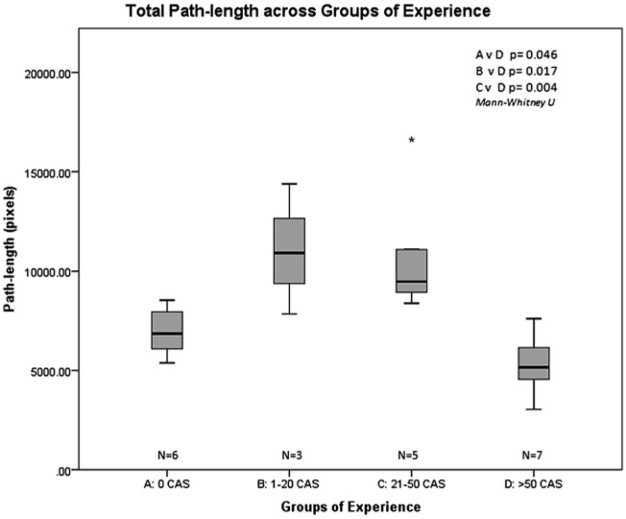

Figure 3. Box-plot representing PL (*y*-axis) taken to complete the carotid stenting task across groups of varying experience (*x*-axis) (Kruskal—Wallis $p = 0.02$). The whiskers represent extreme values and the stars the outliers.

Path-length differences between groups of experience; procedural breakdown into phases

Absolute median path-length values are given for each procedural phase according to the previously-defined groups of experience in Table 1. *P* values are given for analysis of distributions, and where relevant following post-hoc analysis. Path-lengths for the different groups of experience are clustered according to procedural phase in Fig. 4.

Correlation of path-length with rating scales and simulator-derived metrics

Out of all participants, the median procedure-specific CAS score (Fig. 5a) achieved was 25/35 (13—33) and correlation with PL demonstrated a statistically significant inverse relationship ($p = 0.014$, rho $= -0.567$). Correlation of PL with the general endovascular rating scores (Fig. 5b) (median: 29/45 (20—40) also demonstrated a significant inverse relationship ($p = 0.027$, rho $= -0.519$)).

Correlations of PL with simulator-recorded errors ($p = 0.097$, rho $= 0.403$), contrast volume used ($p = 0.938$, rho $= -0.028$), total procedure time ($p = 0.08$, rho $= 0.42$), total fluoroscopy time ($p = 0.053$, rho $= 0.463$), and number of cine-loops used ($p = 0.578$, rho $= 0.141$) were not found to be statistically significant.

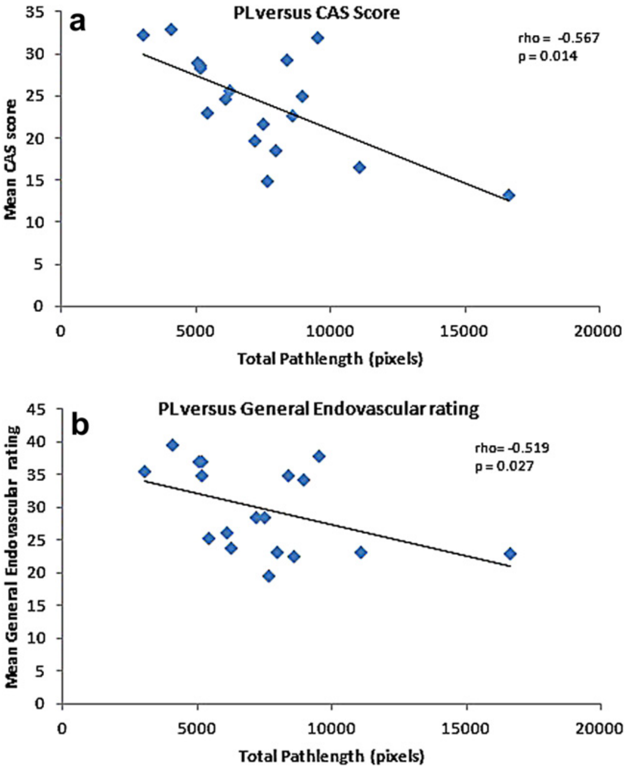

Figure 5. a) and b): Scatter plots showing PL correlations with Total CAS score and General Endovascular Rating, respectively. PL is given on the *x*-axis and assessment scores on the *y*-axis. Individual scores are indicated by the blue diamonds.

DISCUSSION

Path-length calculations have previously been employed in laparoscopic surgery and have been able to discriminate between levels of experience.[7] This study has demonstrated that it is feasible to track endovascular tools on recorded angiography screens and determine PL to assess of endovascular skill. To our knowledge, this is the first study to demonstrate the feasibility of video-based guide-wire tracking using angiography images, specifically. Other tracking tools have employed the use of electro-magnetic,[8] ultrasound[9] and magnetic-resonance based mechanisms.[10] These, however require significant modification of the tip of the endovascular tool as well as the operating room/angio suite. The advantages of this technology include the ability to provide an OBJECTIVE assessment metric that may be improved to become fully automated, and potentially provide real-time feedback to trainees and assessors. Existing qualitative rating scales require time-consuming live assessment or post-hoc video analysis by experts and assignment of numerical values to statements which may introduce an element of subjectivity. It has been observed previously that edited video assessment appears to reduce the reliability of this tool and therefore a short cut to viewing entire procedures seems unreliable.[11] Other methods to track endovascular tools employing position sensors require direct modification of devices in order to facilitate tracking. This may cause interference with the existing mechanical properties of catheters and wires.

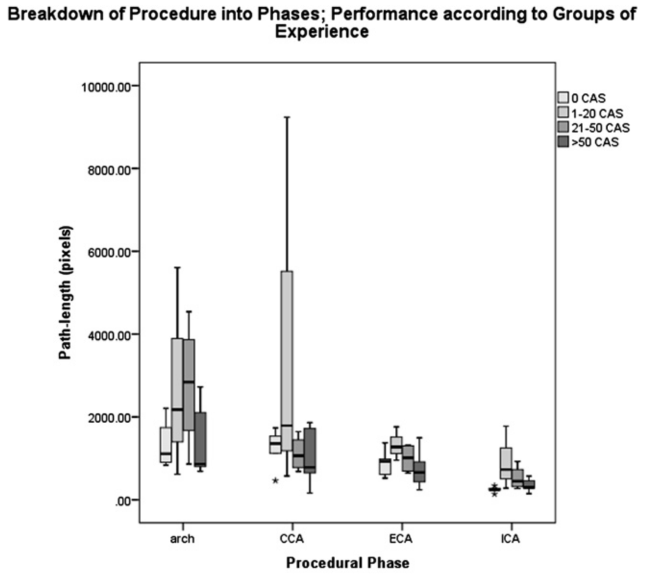

Figure 4. Cluster box-plot demonstrating procedural phase-breakdowns. Each phase given on the *x*-axis is divided into clusters giving PL for that phase according to experience.

This study has shown that guide-wire/catheter tip PL differs between three groups of experienced endovascular therapists with varying CAS experience. Total procedure PL seems to be significantly reduced for the most experienced operators when compared to those who have performed less than 50 CAS cases. Path length was also able to differentiate the highly-experienced (>50 CAS) group from inexperienced (0 CAS), low-volume (1—20 CAS), and moderate-volume (21—50 CAS) groups. Of note, the low- and moderate-volume groups (B and C) exhibited the highest PL values for total procedure, arch navigation and ICA measurements. A similar pattern was observed in these groups for procedure and fluoroscopy time. These previously validated metrics are automatically given by the VIST simulator, and the same pattern has been observed in a previous publication.[1] This pattern was not observed with the rating scale assessments; both the intermediate and highly experienced groups attained significantly higher scores on the generic rating scale than the inexperienced group. The proposed explanation for this observation may be that the novice group attempted to perform the simulated task as quickly as possible with few movements without necessarily appreciating the dangers of such an approach, whilst the moderately experienced groups attempted to complete the task in a more exploratory fashion, moving the guide-wire more frequently when searching for the optimal cannulation strategy. This also translates into increased fluoroscopy and longer procedure times. This theory is supported by a study which evaluated the performance of junior, intermediate and highly experienced surgeons on a virtual reality iliac stenting model before and after receiving cognitive skills training.[12] The investigators found that cognitive skills training significantly increased total procedure and fluoroscopy time, but reduced percentage of residual stenosis, suggesting that more attention was paid to quality outcomes rather than faster task completion.

In the present study, we observed statistically significant correlations between PL and general endovascular/procedure specific rating scales which strengthens the hypothesis that PL may be a useful adjunct to endovascular skills assessment. No significant correlations were seen between PL and simulator-derived metrics (total procedure and fluoroscopy time, contrast volume, errors, and number of cine-loops). It is worth noting that simulator-derived metrics and error scoring in previous studies have yielded inconsistent results in terms of construct validity.[1,13–15]

Motion analysis during the different phases of the CAS procedure demonstrated that PL during arch navigation, CCA cannulation and ECA manipulation was lowest in the highly experienced group, however this did not achieve statistical significance, most likely due to the small numbers in this sub group analysis. For CCA cannulation in particular, we observed a non-significant but step wise reduction in PL with increasing experience, with the exception of the low-volume group who had the longest PL. Small numbers in this group may not accurately reflect this level of experience. For ICA manipulation the most inexperienced group had the shortest PL. A possible explanation for this relates to the fact that inexperienced subjects are less aware of the potential hazards of crossing the lesion with the embolic protection device. With experience, endovascular manipulation in this phase involves careful and measured set-up in the CCA before attempting lesion crossing. The technical challenge presented during CCA cannulation is another factor to consider; with progressive expertise less movement is required to complete this phase. A technically less demanding — but no less important-phase of the procedure such as ICA lesion crossing which involves simple advancement of the guide-wire/monorail system may be less discriminatory and therefore doesn't demonstrate linear relationship between experience and PL on final analysis. Further work is required to determine whether CCA cannulation analysis alone during CAS may be able to discriminate technical skill more accurately and objectively compared to other phases of the procedure.

A potential limitation of this study relates to motion analysis of a three-dimensional (3D) procedure on a two-dimensional (2D) image. Aspects of the catheter motion out of the *x* and *y* planes will not be captured using our method. Whilst this clearly produces an error in calculation of PL, it is balanced by the fact that this method may be applied to live and simulated cases without the need for tool modification, but via simple recording of the angiography screen. Also one may argue, that the majority of current endovascular techniques in the clinical setting are performed utilising 2D fluoroscopy. Furthermore, the motion/PL output, at present, from the software analysis is measured in pixels. There is therefore some difficulty in interpreting these results and the real distances are not known. In addition, the current software does not account for changes in image magnification during C-arm manipulation during live cases, and ensuing errors in PL measurement have to be manually corrected. Phases during which the fluoroscopy view was changed were not tracked in an attempt to limit "non-operator dependent" PL data being captured; which may have led to valuable descriptive motion data. Our group is currently focussing on further software development to address these limitations. Simulator software errors were also evident and included unintentional endovascular tool movements, removal of endovascular tools and occasionally tool duplication on the simulator screen. Such errors were corrected for during final analysis by removing raw pixel co-ordinate data identified as being a software-generated error. Lastly, groups were small and divided arbitrarily according to CAS experience, which may not necessarily represent actual expertise.

While path-length measurement does not represent the entirety of endovascular skill assessment, full automation and further evaluation in a study of live cases will hopefully result in the refinement of an objective skill metric which will accurately and efficiently define expert performance in terms of movement, and will complement existing metrics. Further development of video-motion analysis in general as a medium for skills assessment has the potential for identification of additional motion-descriptive metrics.

CONCLUSION

This pilot study has demonstrated that semi-automated endovascular tool PL measurement is feasible using fluoroscopy images. The motion path-length appears shorter for highly experienced operators during CAS procedures on the VIST simulator and there are significant correlations between PL and qualitative video-based rating scores. Path-length measurement may represent a useful adjunct to existing endovascular skills assessment tools.

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ETHICAL APPROVAL

Not applicable.

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AUTHORSHIP

Concept and design: AR, CB, CR, DS, NC.
Acquisition of data: AR, CS, IVH.
Analysis and interpretation: AR, CB, MH.
Drafting of article and critical revision: AR, CB, CR, IVH.
Final Approval: CB.

CONFLICT OF INTEREST

No conflict of interest.

REFERENCES

1 Van Herzeele I, Aggarwal R, Choong A, Brightwell R, Vermassen F. Virtual reality simulation objectively differentiates level of carotid experience in experienced interventionalists. J Vasc Surg 2007;46:855—63.

2 Van Herzeele I, Aggarwal R, Neequaye S, Hamady M, Cleveland T, Darzi A, et al. Experienced interventionalists objectively improve their skills by attending carotid artery stent training courses. Eur J Vasc Endovasc Surg 2008;35:541—50.

3 Dawson DL, Meyer J, Lee ES, Pevec C. Training with simulation improves residents' endovascular procedure skills. J Vasc Surg 2007;45(1):149—54.

4 Van Herzeele I, Aggarwal R, Malik I, Gaines P, Hamady M, Darzi A, et al. Validation of video-based skill assessment in carotid artery stenting. Eur J Vasc Endovasc Surg 2009;38:1—9.

5 Martin JA, Regehr G, Reznick R, MacRae H, Murnaghan J, Hutchison C, et al. Objective structured assessment of technical skill (OSATS) for surgical residents. Br J Surg 1997;84(2):273—8.

6 Datta V, Mackay S, Mandalia M, Darzi A. The use of electromagnetic motion tracking analysis to objectively measure open surgical skill in the laboratory based model. J Am Coll Surg 2001;193:479—85.

7 Aggarwal R, Crochet P, Dias A, Misra A, Ziprin P, Darzi A. Development of a virtual reality training curriculum for laparoscopic cholecystectomy. Br J Surg 2009;96:1086—93.

8 Manstad-Hulaas F, Tangen GA, Gruionu LG, Aadahl P, Hernes TA. Three-dimensional endovascular navigation with electromagnetic tracking: ex vivo and in vivo accuracy. J Endovasc Ther 2011;18(2):230—40.

9 Bond AE, Weaver FA, Mung J, Han S, Fullerton D, Yen J. The influence of stents on the performance of an ultrasonic navigation system for endovascular procedures. J Vasc Surg 2009;50(5):1143—8.

10 Kurpad KN, Unal O. Multimode intravascular RF coil for MRI-guided interventions. J Magn Reson Imaging 2011;33(4): 995—1002.

11 Scott DJ, Rege RV, Bergen PC, Guo WDA, Laycock R, Tefsay ST, et al. Measuring operative performance after laparoscopic skills training: edited videotape versus direct observation. J Laparoendosc Adv Surg Tech A 2000;10:183—90.

12 Van Herzeele I, Aggarwal R, Neequaye S, Darzi A, Vermassen F, Cheshire NJ. Cognitive training improves clinically relevant outcomes during simulated endovascular procedures. J Vasc Surg 2008;48:1223—30.

13 Aggarwal R, Black SA, Hance JR, Darzi A, Cheshire NJ. Virtual reality simulation training can improve inexperienced surgeon's endovascular skills. Eur J Vasc Endovasc Surg 2006;31(6):588—93.

14 Berry M, Reznick R, Lystig T, Lonn L. The use of virtual reality for training in carotid artery stenting: a construct validation study. Acta Radiol 2008;49(7):801—5.

15 Tedesco MM, Park JJ, Harris EJ, Krummel TM, Dalman RL, Lee JT. Simulation-based endovascular skills assessment: the future of credentialing? J Vasc Surg 2008;47(5). 1008—1.