The Use of Video-motion Analysis (VMA) to determine the Impact of Anatomic Complexity on Endovascular Performance in Carotid Artery Stenting

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ABSTRACT

OBJECTIVE Video-motion analysis (VMA) uses fluoroscopic sequences to derive information on catheter and guide-wire movement, and is able to calculate 2D catheter-tip path-length (PL) on the basis of frame-by-frame pixel coordinates. The objective of this study was to evaluate effect of anatomical complexity on the efficiency of completion of defined stages of simulated carotid artery stenting (CAS), as measured by video-motion analysis (VMA).

METHODS Twenty interventionists each performed a standardised easy, medium, and difficult CAS case in random order on an Angiomentor^{TM} simulator. Videos of all procedures were analysed using VMA software, and performance was expressed in terms of 2D guide-wire tip trajectory distance (PL). Comparisons of PL were used to identify differences in cannulation performance of the participants between the three cases of varying difficulty. The procedure was sub-divided into four procedural phases; arch navigation, common carotid artery cannulation (CCA), external carotid manipulation and carotid lesion crossing. Comparisons of PL were used to identify differences in performance between the three cases of varying difficulty for each of the procedural phases.

RESULTS There were significant differences in PL in relation to anatomic complexity, with a step-wise increase in PL from easy to hard cases [easy: median 5000 pixels (IQR: 4075-5403), vs intermediate: 9059 (5974-14553), vs difficult: 17373 (IQR: 11495-26594), p=<0.001]. Similarly, during CCA cannulation, there was a step-wise increase in PL from easy to hard cases [easy: 749 (603-1403), vs intermediate: 3274 (1544-8142), vs difficult: 8845(5954-15768), p=<0.001]. There were no observed differences across the groups of anatomic difficulty for the phases of arch navigation, external carotid manipulation and carotid lesion crossing

CONCLUSIONS Increasing anatomic complexity leads to significant increases in PL of endovascular tools, in particular during CCA cannulation. This increase in tool movement may have a bearing on clinical outcome.

INTRODUCTION

Carotid intervention remains one of the most debated and researched facets of vascular surgery. Evidence suggests that embolisation occurs during wire and catheter manipulation in the aortic arch and cannulation of the supra-aortic vessels prior to the deployment of a protection device[1]. Anatomic complexity has been proposed as a possible factor contributing to procedural stroke risk, since it may in theory make the task of safely catheterising the target vessels more challenging[2-4]. The relationship between anatomical complexity and efficiency of tool manipulation and movement within the vasculature remains poorly understood. Video-motion analysis (VMA) in endovascular surgery is a relatively new concept and has been investigated as a means of analysing efficiency of performance. Initial studies have found that it can differentiate skill levels in simulated CAS and in live coronary intervention[5,6]. We use three simulated CAS cases of increasing complexity as judged by a validated scoring system[7], with the aim using VMA to investigate the effect of anatomical complexity on endovascular performance and efficiency in CAS.

METHODS

Participants

Ethical approval was obtained for this study. Twenty interventionists from a diverse range of specialties (interventional radiology, vascular surgery and neuroradiology) participated in the study. All participants were formally consented. VMA was performed on videos of patient-specific CAS simulations provided by a collaborating unit, and task set-up and participant recruitment are attributed to this group[8]. The following inclusion criteria in terms of minimal experience were applied:

-Five arch and/or visceral and/or peripheral vessel angiographies, and/or

-Five angioplasty and/or stenting procedures of extra-cranial, visceral, or peripheral arteries, and/or

-Five abdominal aortic or thoracic endovascular aneurysm repairs and/or contralateral limb cannulations

Participant endovascular experience is given in table I.

AngioMentor simulation device and patient-specific reconstructions

VR-simulation has evolved to allow for incorporation of patient-specific CT- and MR-DICOM data into computer-based simulation devices such as the AngioMentor™ (Simbionix, Airport City, Israel), facilitating case simulations based on real anatomy and procedure-specific rehearsals[9,10]. Three-dimensional (3D) reconstructions of three real patient cases, each representing a different level of anatomical complexity[8]- as proposed in the anatomic scoring system developed by MacDonald et al[7]- were created using Simbionix PROcedure rehearsal studio software (Simbionix USA Corp, Cleveland, OH, USA). The anatomic scoring system was developed using a survey and describes 12 different anatomic features including arch configuration, target vessel and tortuosity, and vessel calcification. Each anatomical feature was assigned a score from 1 to 9, and a scoring grid was ultimately developed with 96 different anatomical combinations. Finally all combinations were stratified into green (easy cases- score: <4.9), amber (medium cases- 5-5.9), and red (hard cases- >7.0) (fig. 1). The reconstructions used in this study were based on real patient CT-angiogram DICOM data. The AngioMentor Express simulator (Simbionix USA Corp) was used to perform the training cases and the three simulated patient-cases[8]. The cases were acquired from a pre-existing database of 3D reconstructions stored on the Simbionix PROcedure rehearsal studio software. Clinical and radiological features were as follows[8]:

Green case- 72-year-old man with a type I arch and an asymptomatic 90% stenosis of the left internal carotid artery (LICA). The anatomic score for this case was 2.4 (fig. 1).

Amber case- 82-year-old man with acute aphasia and an 80% stenosis of the left ICA. The case was characterised further by an angled left common carotid artery take-off and bovine arch morphology. The anatomic score was 5.9.

Red case- 82-year-old woman with a symptomatic right-sided 80% internal carotid artery stenosis. The aortic arch was classified as having type II morphology with a very tortuous common carotid artery, although its take-off was not described as angulated.

Task performed

Prior to the actual data collection, all participants underwent standardised training in CAS. Participants attended a 25-minute video lecture on carotid artery disease and stenting. The video itself was approved by two independent CAS experts for content and quality. The technical training consisted of three 90-minute sessions. The novice interventionists were trained in the steps of trans-femoral CAS using filter protection with a preset generic virtual CAS case available on the simulator. Subsequent challenging generic cases, consisting of a bovine arch and Type III arch, allowed for skills acquisition in different techniques of cannulation, using an array of endovascular tools.

After completing the cognitive and technical training sessions in CAS, all participants were enrolled into the study within 5 days. Each participant performed three cases (green, amber and red) during one session in a random order to avoid any residual learning effect. Five-minute intervals were scheduled between each case.[8] Catheter choice was left to the participant in all cases.

Catheter-tracking software

The catheter tracking software has been described previously[5,6], so an abbreviated description is given here: 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. After an initial tracking point is selected by the user, the software then estimates the catheter or guide-wire tip's position in subsequent frames using a semi-automatic tracking scheme that probes the immediate pixel field around the tracking marker for a similar pattern of pixellation. The software generates pixel co-ordinates for each frame based on the catheter-tip's position and calculates 2D movement (path-length or PL) using cumulative frame-by-frame co-ordinate data, which is expressed as movement in pixels. In all videos the distal-most tip of the guide-wire/catheter interface (either the guide-wire or the catheter) was tracked. The software has demonstrated robust inter-observer reliability in previous studies[5,6]. The protocol for tracking in this experiment is given in the sub-section below.

Task analysis

Post-hoc video analysis of all procedures (n=60) was performed by a blinded assessor using the VMA software described above. Only phases of active movement were tracked, and phases of angiographic image manipulation (such as C-arm rotation and "table" movement) were not analysed in order to avoid incorporation of movement artefact into the final PL analysis. Each case was sub-divided into four pre-defined procedural phases (fig. 2). Arch Navigation was defined as movement of the guide-wire and catheter from the level of the 3rd rib to a resting position at the aortic root. Common carotid artery cannulation (CCA) was defined as movement from the aortic root to a stable position 2 cm distal to the common carotid ostium. External carotid artery manipulation (ECA) was defined as movement from 2 cm within the CCA to the distal-most segment of the ECA. Internal carotid artery manipulation (ICA)/lesion crossing was defined as movement from 2 cm within the CCA to the position at which the embolic protection device was deployed.

For each simulation the wire/catheter-tip PL was calculated for the entire procedure as well as each of the procedural phases, and was expressed as pixels of movement. Qualitative procedural rating scales were obtained for comparison with PL: The fluoroscopy screen and hand movements of the interventionist during all simulated CAS procedures were video-taped. These videos were reviewed post-hoc independently (IvH, WW) to assess the quality of the interventionists' performance using a validated Generic Endovascular Rating Scale (GRS) and a Procedure-Specific CAS Rating Scale (PSRS)[11], and an average score was calculated. Therefore, each procedure was awarded an average CAS-specific- and Generic Endovascular Rating score. The experts were blinded to the identities of the interventionists. As described in previous publications, both of these rating scales were derived from the original Reznick qualitative rating scale[12]. Each domain of endovascular skill is scored on a Likert scale around descriptive comments which serve as anchor points for scores 1 (very poor), 3 and 5 (clearly superior). There are eight domains in the Generic Rating Scale, giving a maximum score of 40, and seven domains in the Procedure Specific Score, giving a maximum score of 35. The Procedure-Specific Rating Scale was designed to assess the key components of the CAS procedure, such as cannulation of target vessels and also allows the assessor to rate the quality of the final product and the overall performance.

Statistical analysis

Data were analysed with the Statistical Package for Social Sciences 22.0 (SPSS, Chicago, Ill). The data was not normally distributed, therefore non-parametric tests were used. *Friedman's test* was used to assess repeated (Green, Amber and Red cases) total procedural PL measurements, and procedural phase PL measurements across the same group of interventionists. Pre-defined post-hoc comparisons of PL between the different grades of anatomical complexity were performed -when a significant difference was identified with *Friedman's test*- using the *Wilcoxon-signed rank test*. Correlations between PL and Generic- and Procedure-Specific Rating Scales, as well as individual domains of these rating scales were performed using *Spearman's rank correlation coefficient*. In order to investigate PL as a potential *qualitative* metric, total PL was correlated with generic qualitative descriptors for the entire procedure; "respect for tissue", "flow of procedure", and "handling of endovascular instruments". PL for specific procedural phases (CCA cannulation and lesion crossing/ICA manipulation) were correlated with the domains of "catheterisation" and "lesion crossing", in order to evaluate the metric as a descriptor for the quality of individual procedural phases. A level of $p < 0.05$ was considered to be statistically significant. Given that CAS experience was low across the group of interventionists, total endovascular experience (total number of cases performed- as recorded in logbooks) was correlated with the cumulative total PL for the three cases (Green, Amber, Red) for each individual interventionist using *Spearman's rank correlation coefficient*.

RESULTS

It was feasible to track path-length of endovascular tools using videos derived from the AngioMentor simulator. Typical graphical representations of path-lengths for each of the grades of anatomical difficulty can be seen overlain onto the angiographic image (fig.3).

Total Path-length differences between the cases of varying anatomical complexity

There were significant step-wise increases in total path-length with increasing anatomical complexity (fig.4): The median PL for the green case was 5000 pixels (inter-quartile range (IQR) 4075-5403.2), vs 9059.8 pixels (IQR 5974-14553) vs 17372.9 pixels (IQR 11495-26594) for the amber and red cases, respectively (p = <0.001). Post-hoc analysis with the *Wilcoxon-signed rank test* demonstrated that PL was significantly reduced for green vs amber cases (p = <0.001), and amber vs red cases (p = 0.003).

Path-length differences between the cases of varying anatomical complexity; procedural breakdown into phases

There were significant step-wise increases in path-length with increasing anatomical complexity during CCA cannulation: The median PL for the green case was 748.67 pixels (IQR 603.4-1403.5) vs 3273.6 (IQR 1544.8-8142.4) vs 8844.7 (IQR 5954.5-15767.9) for the amber and red cases, respectively (p = <0.001). Post-hoc analysis with the *Wilcoxon-signed rank test* demonstrated that PL was significantly reduced for green vs amber cases (p = <0.001), and amber vs red cases (p = 0.033). Differences in median path-lengths during the remaining procedural phases were not found to be significant: path-lengths according to traffic-light groupings were 359.9 (green) vs 388.1 (amber) vs 382.8 (red) for arch navigation (p = 0.4), 356.7 vs 329.8 vs 736.7 for ECA manipulation (p = 0.4), and 657.1 vs 635.4 vs 863.2 for ICA manipulation/lesion crossing (p = 0.7).

Correlation of path-length with total endovascular experience

Correlation of total cumulative PL for the three cases (Green, Amber and Red) for each interventionist with total endovascular experience demonstrated a weak, but statistically significant inverse relationship (rho = -0.485, $p = 0.03$).

Correlation of path-length with rating scales

For all procedures across the three grades of anatomic difficulty, the median Procedure Specific Rating Scale score achieved was 21.5/35 (18.6-24) and correlation with PL demonstrated a statistically significant inverse relationship (rho = -0.549, $p = <0.001$), and the median Generic Rating Scale score achieved was 28.2/40 (24.6-30). Correlation of PL with the GRS demonstrated a similar statistically significant inverse relationship (rho = -0.632, $p = <0.001$) (fig.5).

Correlation of path-length with specific domains of rating scales

Total PL was significantly and inversely correlated with the "respect for tissue" (rho = -0.510, $p = <0.001$), "handling of endovascular material" (rho = -0.483, $p = <0.001$), and "flow of procedure" (rho = -0.713, $p = <0.001$) domains. PL for CCA cannulation was strongly and inversely correlated with the "catheterisation phase" (rho = -0.672, $p = <0.001$). A weaker correlation between ICA manipulation/lesion crossing PL and "lesion crossing phase" was identified (rho = -0.273, $p = 0.035$).

DISCUSSION

This study documents the direct relationship between anatomic complexity and efficiency of catheter and guide-wire movements in CAS. Furthermore, it has provided evidence to demonstrate that challenging arch and target vessel configurations significantly impede cannulation attempts, resulting in a step-wise increase in total path-length measurements for the entire procedure with progressive anatomical complexity. Moreover, when the CAS procedure was deconstructed into a series of procedural phases, it was apparent that the CCA cannulation phase demonstrated a similar significant step-wise increase in PL with progressive anatomic complexity. The phases of arch navigation, ECA and ICA manipulation did not demonstrate any significant differences, although there was a trend towards reduced efficiency as measured by PL in the red cases for the two latter procedural phases. Figure 3 demonstrates that challenging CCA cannulation, in addition to repetitive movement at the origin of the target vessel, causes excessive movement in the ascending aorta, proximal to the target vessel.

Anatomical variation has been proposed as a significant factor that contributes to challenging CAS procedures[7], and in theory may increase the likelihood of embolisation. Data relating rates of embolisation and anatomical configuration are fairly limited and heterogeneous in terms of anatomic factors studied. A recent sub-study derived from ICSS data suggests that adverse anatomic features (type 2/3 aortic arches, ICA angulation $>60^0$) are associated with the development of new ischaemic lesions on MRI scanning[4]. Similarly, Nagarra and colleagues evaluated digital subtraction angiograms from the EVA-3s trial and found angulation of the ICA in relation to the CCA ($>60^0$) to be the only independent anatomical factor to significantly affect 30-day ipsilateral stroke risk[2].

In the present study, adverse CCA configuration appeared to be the main discriminator in terms of efficiency of cannulation and is supported by the observation that path-length for CCA cannulation was significantly and strongly correlated with the "catheterisation phase" rating. We observed that challenging CCA cannulation resulted in excessive movement within the arch. Relating this finding to existing clinical data is challenging, given the paucity of available data, however Cao and colleagues found that of eight disabling strokes in a series of 301 procedures, four occurred during arch navigation and cannulation of the supra-aortic vessels and four during the stent-implantation and ballooning[1].

Whilst this study does not seek to- and cannot provide data on embolisation in relation to anatomic variation, it clearly demonstrates that the most "challenging" case (type II arch and tortuous CCA) is associated with increased endovascular tool manipulation prior to lesion crossing, enhancing understanding of how adverse anatomy may affect outcomes. Further work with real-time monitoring of embolic events, for instance with trans-cranial Doppler monitoring, is required to clearly underpin the relationship between anatomy, tool movement, and embolisation.

Given these findings, potential future applications might include application of the VMA technique in pre-procedure case rehearsal as a means of identifying the relative safety, or conversely, the risks of undertaking endovascular intervention in anatomically challenging carotid cases[9,13]. Furthermore, the technology could potentially be used to evaluate the competencies of operators in more complex cases, and be used for training and credentialing of operators for such cases. One might argue that an experienced interventionist would be able to identify challenging anatomy simply by looking at the pre-operative CT. However, the use of VMA in conjunction with patient-specific pre-procedure rehearsal would allow for accurate mapping and documentation of “problem” areas and inform on optimal cannulation strategies. Armed with specific knowledge as to where a particular operator experienced difficulties, the operator might select different catheters and strategy and try these out on a repeated rehearsal. This is particularly relevant in the training setting, and would allow the supervisor to identify alternative strategies, or indeed, evaluate the suitability of the case for training.

A potential weakness of this study is the subtle variation in terms of vessel lengths across the three different reconstructions. Given the anatomical variability of a typically tortuous structure such as the ECA, it was challenging to accurately define and standardise start- and end-points for PL measurements across the three cases. Consequently, variation in terms of PL output for this vessel and the ICA may be significantly related to vessel length itself rather than impact of tortuous anatomy on efficiency of tool manipulation. One might argue therefore that variations in PL during navigation through small-diameter vessels, which allow only for axial movement up and down the length of the vessel, are more a direct measurement of the anatomy itself. In comparison, variation in PL during cannulation of challenging target vessels arising from a large-calibre vessel such as the aorta may more accurately reflect the impact of skill and anatomical variation on efficiency of tool manipulation. Additionally, subtle variation in terms of PL output between individual interventionists was expected on the basis of differences in catheter selection.

This study evaluated the impact of anatomical complexity on the endovascular performance of a group of operators who had moderate general endovascular experience but who were inexperienced with CAS. The findings are therefore applicable to interventionists who are on a CAS learning curve, and emphasize the need for pre-procedure rehearsal with VMA to identify procedural phases that are likely to present a technical challenge. As mentioned above, potential applications would be the credentialing of such interventionists and the use of VMA to aid in appropriate case selection. Further investigation could also now be directed on the impact of anatomical adversity on the performance of experienced CAS interventionists. This would facilitate the examination of an experienced cohort in terms of advanced techniques used to overcome challenging anatomy and reduce the potential for embolisation.

CONCLUSION

Increasing anatomical complexity in CAS leads to significant increases in path-length during endovascular manipulation. Efficiency of CCA cannulation in this study is strongly influenced by challenging anatomical features such as tortuosity and angulation with respect to the aortic arch. Excessive, prolonged and inefficient movements during manipulation, especially during CCA cannulation, may in part explain the increased embolisation risk associated with anatomically challenging cases.

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REFERENCES

1. Cao P, De Rango P, Verzini F, Maselli A, Norgiolini L, Giordano G. Outcome of carotid stenting versus endarterectomy: a case-control study. *Stroke*. 2006; 37: 1221–1226.

2. Naggara O, Touze E, Beyssen B, Trinquart L, Chatellier G, Meder JF, et al. Investigators. Anatomical and technical factors associated with stroke or death during carotid angioplasty and stenting: results from the endarterectomy versus angioplasty in patients with symptomatic severe carotid stenosis (EVA-3S) trial and systematic review. *Stroke*. 2011; 42: 380–388.

3. Sayeed S, Stanziale SF, Wholey MH, Makaroun MS. Angiographic lesion characteristics can predict adverse outcomes after carotid artery stenting. *J. Vasc. Surg.* 2008; 47: 81–87.

4. Müller MD, Ahlhelm FJ, von Hessling A, Doig D, Nederkoorn PJ, Macdonald S, et al. Vascular Anatomy Predicts the Risk of Cerebral Ischemia in Patients Randomized to Carotid Stenting Versus Endarterectomy. *Stroke.* 2017; 48: 1285-1292

5. Rolls AE, Riga CV, Bicknell CD, Stoyanov DV, Shah CV, Van Herzeele I, et al. A pilot study of video-motion analysis in endovascular surgery: development of real-time discriminatory skill metrics. *Eur. J. Vasc. Endovasc. Surg.* 2013; 45: 509–515.

6. Rolls AE, Riga CV, Rahim S, Stoyanov D, Van Herzeele I, Mikhail G, et al. Video-motion Analysis in Live Coronary Angiography differentiates levels of experience and provides a Novel Method of Skill Assessment. *Eurointervention.* 2017; 13: 1460-1467.

7. Macdonald S, Lee R, Williams R, Stansby G, Delphi Carotid Stenting Consensus Panel. Towards safer carotid artery stenting: a scoring system for anatomic suitability. *Stroke.* 2009; 40: 1698–1703.

8. Willaert W, Cheshire N, Aggarwal R, Van Herzeele I, Stansby G, Macdonald S, et al. Improving results for carotid artery stenting by validation of the anatomic scoring system for carotid artery stenting with patient-specific simulated rehearsal. *J. Vasc. Surg*. 2012; 56: 1763–1770.

9. Willaert W, Aggarwal R, Van Herzeele I, Plessers M, Stroobant N, Nestel D, et al. Role of patient-specific virtual reality rehearsal in carotid artery stenting. *Br. J. Surg.* 2013; 99: 1304–1313.

10. Desender L, Rancic Z, Aggarwal R, Duchateau J, Glenck M, Lachat M, et al. Patient-specific rehearsal prior to EVAR: a pilot study. *Eur. J. Vasc. Endovasc. Surg.* 2013; 45: 639–647.

11. Van Herzeele I, Aggarwal R, Neequaye S, Hamady M, Cleveland T, Darzi A, et al. Experienced Endovascular Interventionalists Objectively Improve their Skills by Attending Carotid Artery Stent Training Courses. *Eur. J. Vasc. Endovasc. Surg.* 2008; 35: 541-550.

12. 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: 273–278.

13. Willaert W, Aggarwal R, Van Herzeele I, O'Donoghue K, Gaines PA, Darzi AW, et al. Patient-specific Endovascular Simulation Influences Interventionalists Performing Carotid Artery Procedures. *Eur. J. Vasc. Endovasc. Surg.* 2011; 41: 492-500