



Deconstructing mastery in colorectal fluorescence angiography interpretation

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Abstract

Introduction Indocyanine green fluorescence angiography (ICGFA) is commonly used in colorectal anastomotic practice with limited pre-training. Recent work has shown that there is considerable inconsistency in signal interpretation between surgeons with minimal or no experience versus those consciously invested in mastery of the technique. Here, we deconstruct the fluorescence signal patterns of expert-annotated surgical ICGFA videos to understand better their correlation and combine this with structured interviews to ascertain whether such interpretative capability is conscious or unconscious.

Methods For fluorescence signal analysis, expert-annotated ICGFA videos ($n = 24$) were quantitatively interrogated using a boutique intensity tracker (IBM Research) to generate signal time plots. Such fluorescence intensity data were examined for inter-observer correlation (Intraclass Correlation Coefficients, ICC) at specific curve milestones: the maximum fluorescence signal (F_{\max}), the times to both achieve this maximum (T_{\max}), as well as half this maximum ($T_{1/2\max}$) and the ratio between these ($T_{1/2}/T_{\max}$). Formal tele-interview with contributing experts ($n = 6$) was conducted with the narrative transcripts being thematically mapped, plotted, and qualitatively analyzed.

Results Correlation by mathematical measures was *excellent* (ICC 0.9–1.0) for F_{\max} , T_{\max} , and $T_{1/2\max}$ (0.95, 0.938, and 0.925, respectively) and moderate (0.5–0.75) for $T_{1/2}/T_{\max}$ (0.729). While all experts narrated a deliberate viewing strategy, their specific dynamic signal appreciation differed in the manner of description.

Conclusion Expert ICGFA users demonstrate high correlation in mathematical measures of their signal interpretation although do so tacitly. Computational quantification of expert behavior can help develop the necessary lexicon and training sets as well as computer vision methodology to better exploit ICGFA technology.

Keywords Indocyanine green · Fluorescence · Angiography · Digital · Quantitative

Indocyanine green fluorescence angiography (ICGFA) has been rapidly adopted across many surgical disciplines [1]. It has become especially established in colorectal anastomosis assessment protocols during laparoscopic- and

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robotic-assisted surgeries due to its potential benefits in diminishing anastomotic leakage and its clinical [2], oncologic [3], and economic [4] impacts. Despite such momentum, including ongoing multinational randomized trials [5], variability in its clinical deployment and study outcomes exists [6, 7]. Previous work by this research collaborative demonstrated considerable inter-user variability in ICGFA interpretation, especially among inexperienced users [8]. In contrast, experienced users displayed better correlation in their decisions regarding geographical determination of colonic proximal transection levels. Better understanding of these observations could facilitate improved utilization of this technology allowing its true value to be extracted by all users.

Therefore, here we follow on the initial observer variability discovery work with a focused investigation of the interpretation and cognitive processes occurring at expert user level in that study via semi-structured interviews as well as detailed quantitative analysis of observed video signal interpretation. The purpose of our study was to evaluate factors underlying the better correlation seen between experts and to establish whether this occurs due to conscious act in order to inform how best to advance ICGFA interpretation among others.

Methodology

Prior study

This research [8] (performed with institutional ethics approval Mater Misericordiae University Hospital, Dublin, Ireland—1/378/2092) involved the presentation of an archived set of edited ICGFA video sequences ($n = 14$, 9 showing perfusion signals at the time of proximal colonic transection, five showing anastomotic/small bowel perfusion) obtained during routine laparoscopic colorectal surgery to both experienced (i.e., those who are highly active clinically and academically in the field of ICGFA, $n = 6$) and inexperienced (i.e., those with minimal or no ICG exposure whether clinically experienced or inexperienced, $n = 34$) observers via an innovative video display and annotation platform (Mindstamp: The Interactive Video Platform www.mindstamp.io). All ICGFA transection perfusion videos demonstrated the white-light tissue appearances as well as the near-infrared (NIR) appearances and an overlay, false-colored view of the NIR signal on the white-light image simultaneously using the Pinpoint Endolaparoscopic Near-infrared system (Stryker®). Using Mindstamp, observers were able to record their interpretations of the fluorescence signal of the proximal colonic segment directly onto the video segment, indicating their choice of stapler positioning across the colon based on their interpretation of the

fluorescence signal. This allowed comparison of interpretations between experienced and inexperienced users and showed significant differences in interpretation between the two groups with experienced users showing higher levels of agreement in signal interpretation.

For this study, the specific sites of transection level selection in four expert-annotated videos from the first study were analyzed to both generate and correlate fluorescence dynamic signal patterns as a time series of intensity to understand better the patterns of recognition of the experienced observers. The four videos chosen were those selected as most optimal for computational assessment regarding minimal camera movement and instrument intrusion. In addition, the same expert participants were interviewed to understand their conscious thought processes in interpreting dynamic fluorescence signals.

For fluorescence signal analysis, videos (30 frames per second) of four intraoperative ICG angiograms used in the prior study were analyzed using a boutique intensity tracker (IBM Research Ireland [9]) to generate quantitative plots over time of the fluorescence signal at the transection points selected by expert users ($n = 6$) (see Fig. 1) (camera movement and instrument intrusion compromised continuous transection point machine-based tracking in the remaining five videos from the prior study and so these were not useable in this work). User-selected regions of interest (ROI) in the white-light view were digitally tracked via surface features and concurrent fluorescence intensity was simultaneously quantified in the corresponding regions of the raw near-infrared feed.

The generated fluorescence intensity data were recorded on Microsoft Excel v2012 (NM, USA). Specific curve milestones identified previously as those most clinically meaningful indicators of appropriate ICGFA perfusion signal [10, 11] were identified and tabulated as metadata. These milestones were the maximum fluorescence signal (F_{\max}), the time required for it to rise to fifty percent of the maximum fluorescence intensity ($T_{1/2\max}$), and the time to achieve the full peak (T_{\max}), as well as the ratio of the two ($T_{1/2}/T_{\max}$) (see Fig. 2). Correlation of these parameters among experts was determined by Intraclass Correlation Coefficients (ICC: two-way mixed model, absolute agreement, single measures) [12] calculated using SPSS v26 (IBM, NY, US). To illustrate expert correlation in comparison to inexperienced user data dispersion, this exercise was also carried out for inexperienced users ($n = 34$) for one video and charted as scatter plots, with Chi-squared confidence ellipses charted to visually demonstrate expert/inexpert clustering of curve features.

Experienced user interviews

To understand any conscious viewing strategy applied by each experienced user in the study, each underwent formal interview conducted by teleconference using a template of open and closed questions relating to specific and general uses of ICG fluorescence with particular reference to signal interpretation (see supplementary information). Responses were recorded, transcribed, and qualitatively assessed via thematic analysis [13] (in short, ideas, concepts, opinions, statements, and descriptions were identified, coded, and grouped by emergent themes and mapped graphically with overarching categories as the stem and individual terms as the roots). In addition, a word cloud was plotted to give a visual summary of the main terminology used following the removal of definite and indefinite articles, determiners, pronouns, names, conjunctions, interjections, adjective pre-modifiers, collective nouns, and pre-prepositions, and prepositions using dedicated software www.wordclouds.com (Zygmomatic, Vianen, The Netherlands). Although not academically quantitative, this method of graphical representation groups commonest words used by size with increasing font size indicating more frequently used terms as a simple visual means of summarizing common words and terms.

Results

Six thousand forty data points per expert ($n=6$) were synthesized from the ICGFA videos ($n=4$).

Fluorescence signal analysis

Once plotted, the quantitative fluorescence curves were analyzed regarding F_{\max} , T_{\max} , $T_{1/2\max}$, and $T_{1/2\max}/T_{\max}$ (see Table 1 and Fig. 1). Application of inter-observer comparative statistics revealed *excellent* (0.9–1.0) levels of correlation among these experienced users regarding peak intensity (F_{\max} 0.925) and chronological flags (T_{\max} 0.938 and $T_{1/2\max}$ 0.925) and *moderate* (0.5–0.75) correlation for the $T_{1/2\max}/T_{\max}$ ratio (0.729).

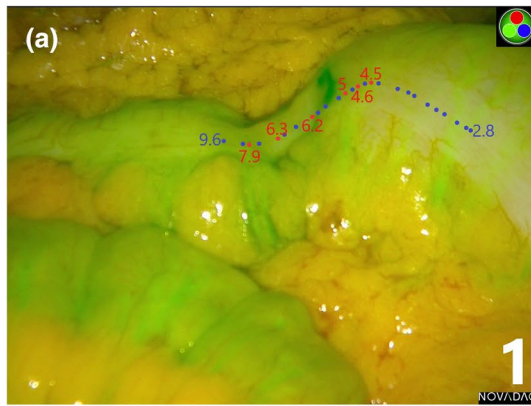
Expert interview data

Structured discussion with each experienced observer demonstrated that each use ICGFA as a confirmatory rather than directive measure with respect to sufficiency of bowel perfusion (i.e., a specific area is being visually evaluated for a reasonable perfusion signal) with a focus on inflow alone and each employs a deliberate interrogative viewing strategy to do so. Furthermore, all advocated a conscious systematic approach to learning including preclinical simulation

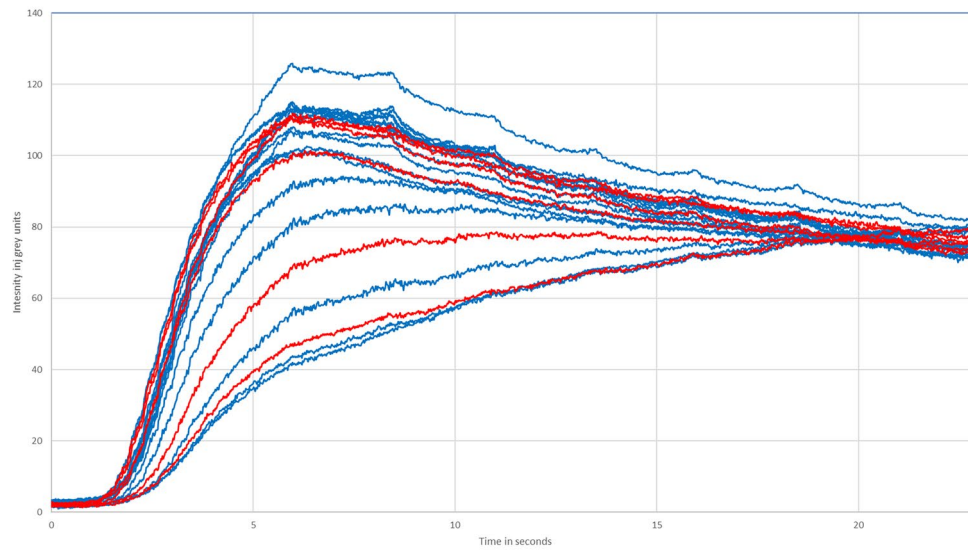
as opposed to operative experiential learning although none had done so themselves or has such a facility in their departments. The experts however described their exact methodology in a variety of ways without common precise terminology (see Figs. 3, 4). Furthermore, more frequent comments were made on methods of ICG set-up rather than its interpretation. While intraoperative redosing and replaying the video were not recommended, a common theme of an ICG ‘time out’ (where the whole theater staff pause to appreciate the ICG signal) was prevalent. There were mixed opinions on the use of composite screen viewing (four utilizing this view) versus viewing the near-infrared signal appearances alone ($n=2$) with the former espousing the benefit of simultaneous interpretation of white-light image appearances. Minimalist systems with fewer options for signal output manipulation were favored. Among considerations other than on-screen fluorescence signal, advocacy for standardization to fixed dosing and administrative method protocols was common with less regard for exact dosing, titration to weight, or ideal signal performance. With respect to inflow signal interpretation, homogeneity of distribution and maximal brightness were prioritized criteria although there was otherwise divergence in opinions re the other proposed criteria. A single expert admitted to using the chronology of the fluorescence as a discrete transection modifying criteria, while two others actively expressed that they did not feel this to be important.

Discussion

Intraoperative decision-making is an empirically learned skill which involves interpretation of visual appearances through judgment based on knowledge and experience. As a dynamic signal, interpretation of ICGFA also requires qualitative interpretation which appears to improve with experience although at present this lacks overt standardization [14] with consensus groups yet to define ideal parameters [15]. This heterogeneity in practice and techniques is also reflected in research studies with some either disregarding [16] or variably appreciating [6, 7] the chronology of the fluorescence intensity. Technical considerations such as ICG-tissue interaction and NIR system performance (including brand specific on-screen display) [17–20] may further impair correct ICGFA perfusion signal interpretation. All of this means that correct interpretation of ICGFA signals may require some experience. Furthermore, the limitation of purely visual analysis drives confirmatory-focused signal appreciation as opposed to full-field exploratory interrogation (i.e., people can only easily look at one region at a time). This work follows on from an initial study [8] that examined if there are differences between experts and inexperienced users regarding ICGFA interpretation using



(b) Temporal fluorescence plot for a representative video for experts(red) vs non experts(blue) at their selected transection points



(c) Labelled curve milestones on ICGFA temporal fluorescence plots

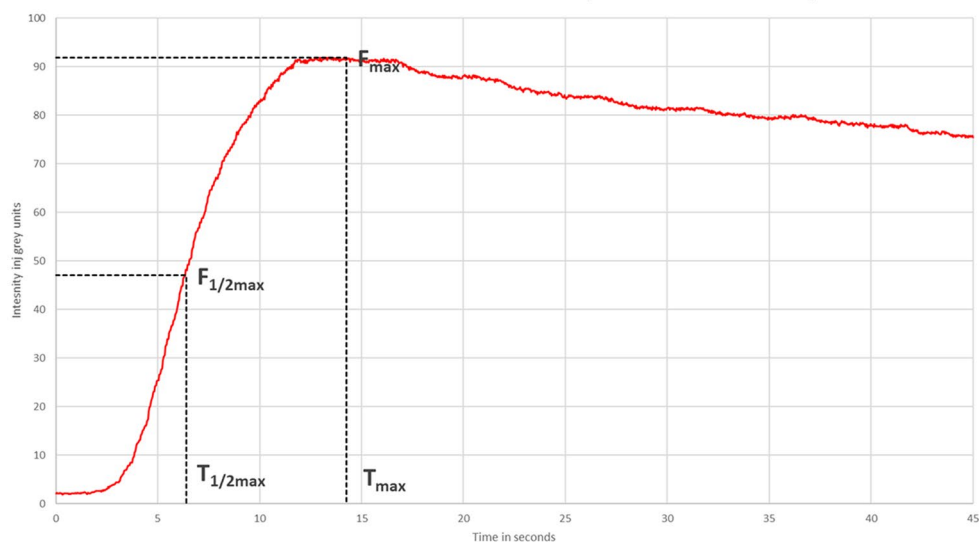


Fig. 1 **a** Transection annotation points on the ascending colon (made on a video recording of anastomotic preparation site during right hemicolectomy) showing experts (red) and inexperts (blue) on a fused NIR and White-light ICGFA still image from the ICGFA video (from [7]) and ascending numbers represent increasing distance (proximal to distal) in mtu (“measuring tool units”) generated using Snip and Sketch, Microsoft, (NM, US) [8]. **b** Quantitative intensity fluorescence time plots charted from these sites, including here, for illustrative purposes, those of inexpert users. **c** Specific curve milestones from an idealized plot selected for the purposes of comparative analysis (Color figure online)

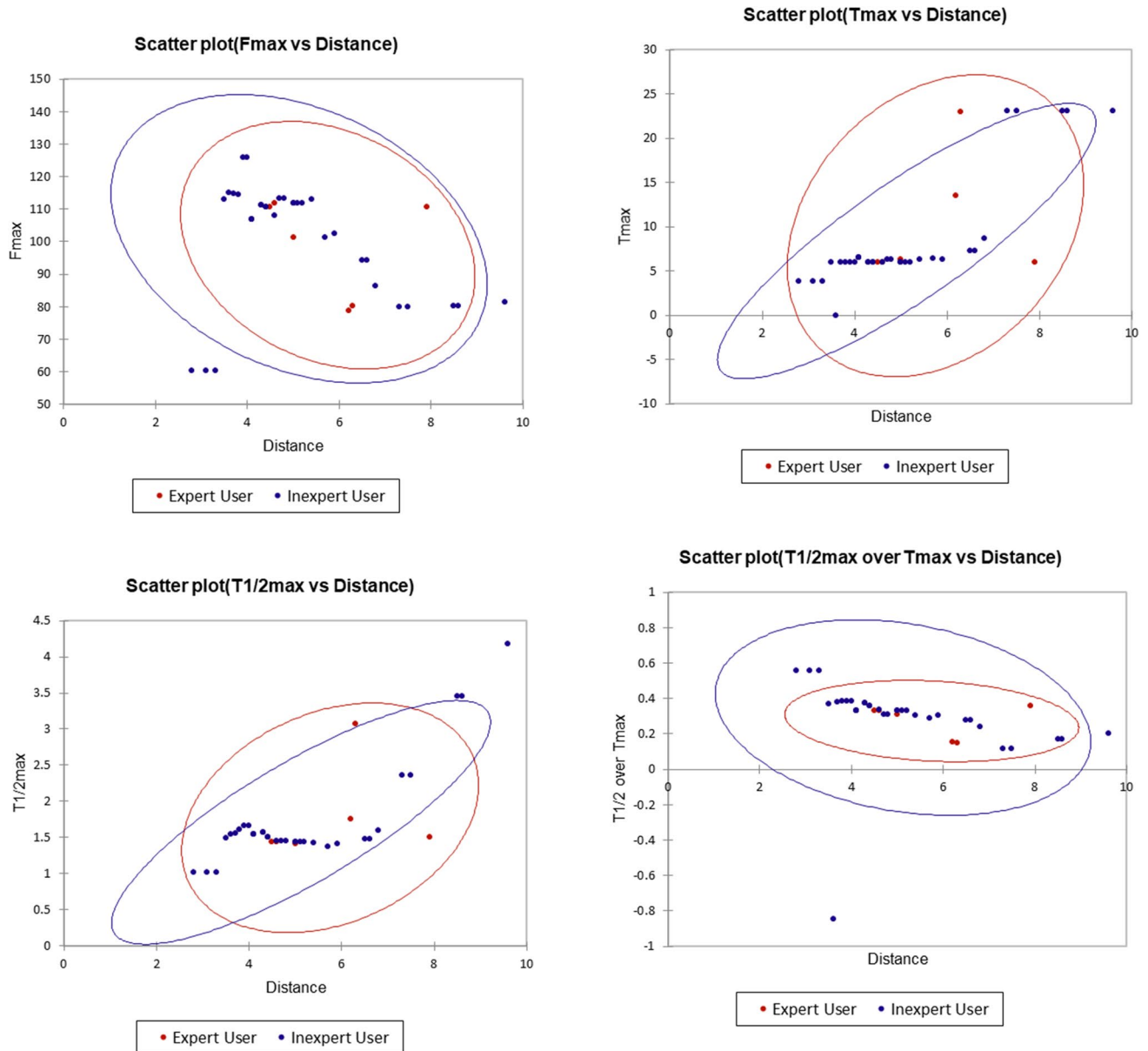
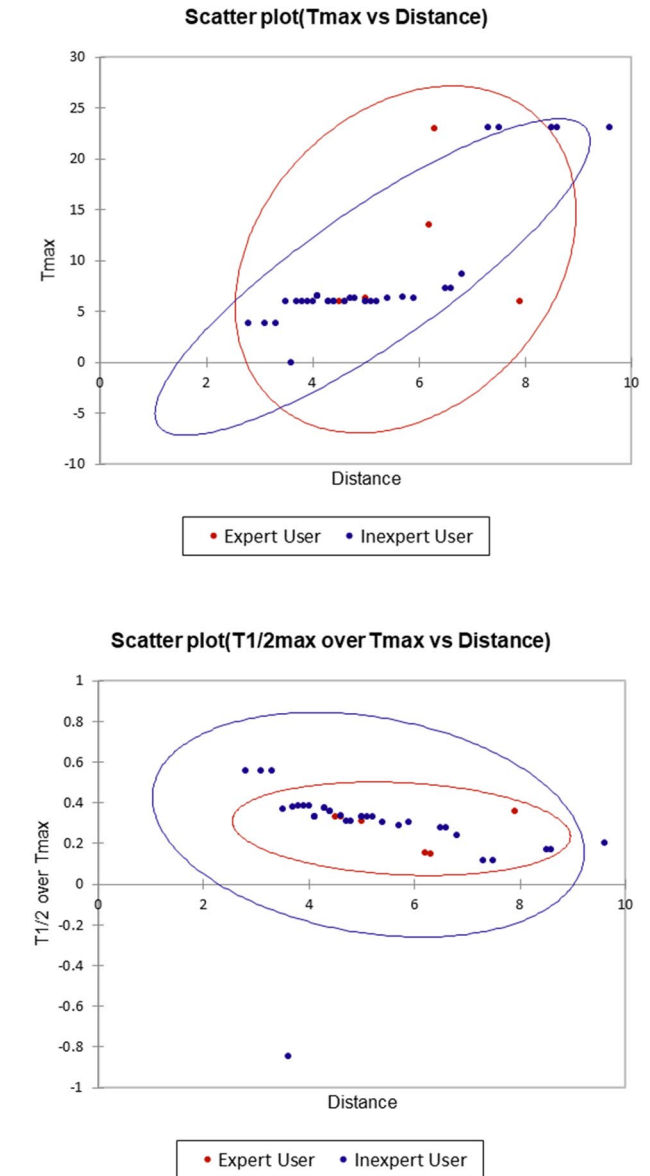


Fig. 2 Quantitative intensity fluorescence plots from expert-annotated video related to transection level (same video as Figure One) are shown here for data illustrative purposes. Plots are tagged for milestones (F_{max} , T_{max} , $T_{1/2max}$ and $T_{1/2max}/T_{max}$) in comparison against those plots associated with inexperts (blue) on the same video. Scatter

temporal fluorescence plots with Chi-squared confidence ellipses (XLSTAT v2021, Addinsoft for Microsoft Excel) for both experts and inexperts are shown with respect to geographical transection point for each predefined curve milestone (Color figure online)



mathematical deconstruction of the dynamic fluorescence signal being viewed.

Main findings

Our experienced users showed excellent tacit agreement in their selections of bowel locations for proximal transections and their selection points were found to have highly similar curve profiles suggesting a common acquired ability to similarly dissect the dynamic signal being observed and flag the most relevant clinical location in a highly concordant fashion. Specifically, the peak intensity (F_{\max}), the time to achieve this zenith (T_{\max}), and the threshold period at which half this incline has been achieved ($T_{1/2\max}$) demonstrated excellent correlation. Interestingly, compound metrics identified experimentally as prognostically sensitive for anastomotic leakage ($T_{1/2\max}/T_{\max}$) [10] resulted in only moderate

correlation. However, despite expert signal interpretation showing great consistency, this was neither consciously appreciated nor reflected in agreement in the recorded interviews. This perhaps should not be too surprising as mastery can often struggle to explain itself in the absence of objective deconstruction and standardized terminology.

Implications for practice

This study's findings do suggest a method for explaining to others how best to extract the most useful information from ICGFA through its observation, perhaps in training libraries that users can study as they accrue their own clinical experience showing patterns of ICGFA signaling at different areas across a screen with indication of where an expert surgeon would choose to affect a clinical decision. Furthermore, the digital deconstruction of

Table 1 Compound table showing comparative data related to temporal fluorescence milestones (generated as metadata from quantitative ICGFA fluorescence time plots at the, respectively, selected

expert colonic geographical transection points across four videos [8]) reported per video and per expert (mean \pm standard deviation)

Temporal fluorescence milestones	Comparison between videos		Comparison between experts			
	Video: Mean \pm s.d		Expert: Mean \pm s.d		Intraclass correlation coefficient	
					Intraclass correlation	95% Confidence interval
F_{\max}			1	98.10 \pm 35.28	0.925 (excellent)	0.740–0.994
	1	99.14 \pm 16.74	2	92.78 \pm 36.22		
	2	147.83 \pm 4.68	3	97.40 \pm 34.68		
	3	68.39 \pm 3.20	4	103.22 \pm 36.43		
	4	80.51 \pm 7.05	5	104.14 \pm 38.91		
			6	98.18 \pm 34.84		
T_{\max}			1	25.65 \pm 13.11	0.938 (excellent)	0.777–0.995
	1	9.69 \pm 6.78	2	27.01 \pm 24.07		
	2	19.70 \pm 0.96	3	26.05 \pm 25.03		
	3	15.37 \pm 1.57	4	26.37 \pm 24.78		
	4	59.53 \pm 7.34	5	26.19 \pm 24.82		
			6	25.16 \pm 25.46		
$T_{1/2\max}$			1	3.83 \pm 2.61	0.925 (excellent)	0.741–0.994
	1	1.76 \pm 0.57	2	4.09 \pm 3.91		
	2	3.10 \pm 0.16	3	3.98 \pm 3.88		
	3	1.69 \pm 0.12	4	4.85 \pm 5.51		
	4	11.00 \pm 2.30	5	4.82 \pm 5.42		
			6	4.76 \pm 5.49		
$T_{1/2\max}/T_{\max}$			1	0.32 \pm 0.15	0.729 (moderate)	0.343–0.976
	1	0.28 \pm 0.08	2	0.30 \pm 0.09		
	2	0.47 \pm 0.05	3	0.32 \pm 0.06		
	3	0.26 \pm 0.05	4	0.35 \pm 0.12		
	4	0.37 \pm 0.06	5	0.36 \pm 0.12		
			6	0.40 \pm 0.09		

Intraclass correlation coefficients between experts (with poor agreement set at <0.5 , moderate at 0.5 – 0.75 , good at 0.75 – 0.9 , and excellent at 0.9 – 1.0) are shown [12]. All the ICC correlation coefficients reported above (F_{\max} , T_{\max} , $T_{1/2\max}$, and $T_{1/2\max}/T_{\max}$) have a significance of $p < 0.001$

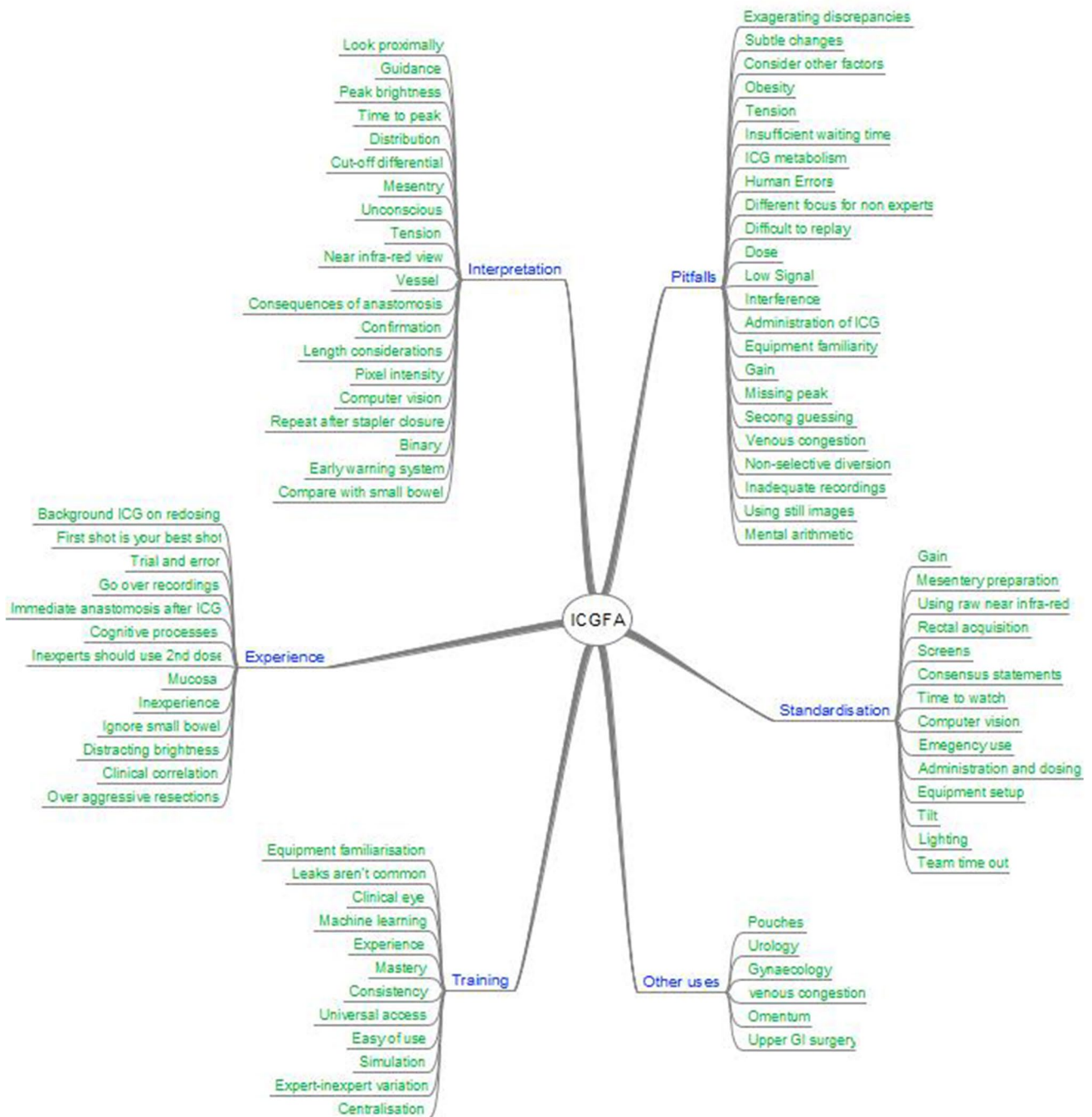


Fig. 3 Thematic map accrued via qualitative analysis [13] of expert interview transcripts ($n=6$). Here expert interview responses were transcribed, and ideas, concepts, opinions, statements, and descrip-

tions were identified, coded, and grouped by emergent themes (the graphical map shows overarching categories as the stem and individual terms as the roots)

ICGFA methodology it uses could also be used for post hoc reflection on trials and experiences most especially those with equivocal or negative results [16]. This study's observations also of course suggest a role for real-time quantitative data synthesis, analysis (including statistical correlation), and display to supplement an observer's own interpretation especially early in their learning curves.

While mathematical flagging of the flow patterns post hoc on operative video recordings could be useful for training curriculums, "on-the-fly" compound computation of fluorescent signals is needed for intraoperative decision support [22]. However the accuracy of such signal plot may be confounded by interpatient [23], variations in ICG pharmacokinetics and pharmacodynamics, as well

speaker fees from Stryker Corp, Medtronic, and Applied Medical. Prof. David Jayne has received consulting honoraria from Stryker Corp. Prof. Ris receives speaker fees from Stryker Corp, Arthrex, Hollister, and Ethicon/J&J and research funding from Ethicon/J&J and Quantgene. Prof. Antonino Spinelli acted as consultant and speaker for Takeda, Pfizer and Janssen, Sofar, and Oasis. Prof. Steven Wexner receives royalties for intellectual property license from Medtronic, Intuitive, and Karl Storz and consulting fees for consulting from Stryker, Intuitive, and Olympus. Dr. Sarah Shanahan has no disclosures.

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