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Original Research

Inexperienced Evaluator Identification of Hand Ischemia Via Video Processed with Pigment-Enhancing Technology

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Purpose: Eulerian video magnification (EVM)+waveform is a novel video processing software that enhances visualization of tissue perfusion and has been shown to improve hand surgeon identification of ischemia via video alone. The purpose of this study is to determine whether EVM+waveform technology will support improved accuracy in identifying hand ischemia for less experienced persons, regardless of the evaluator's health care experience or the melanin content of the hand in the video.

Methods: Healthy volunteers were recruited for us to record videos of their hands both perfused and under tourniquet-induced ischemia. Videos were processed with EVM+waveform and inserted into a 26-question survey. There were two types of questions presented in each survey. One format showed a video processed with EVM+waveform, and the respondent was asked if the hand was ischemic, perfused, or if they were unsure. The second format presented two side-by-side videos, one ischemic and one perfused. Both were processed with EVM+waveform, and the respondent had to choose which was ischemic. Respondents included both medical and non-medical professionals none of whom had experience with hand surgery.

Results: A total of 64 survey responses were recorded. The EVM+waveform technology significantly improved accuracy in determining ischemia regardless of the respondent's health care experience. Respondents were divided into medical doctorate (MD; n = 15) and non-MD (n = 49) groups. Both groups demonstrated significant improvement in determining ischemia when using EVM+waveform. Within the non-MD cohort, accuracy percentages significantly improved across Fitzpatrick types IV, V, and VI. Within the MD cohort, accuracy percentages significantly improved across Fitzpatrick types III, V, and VI.

Conclusions: These findings further establish EVM+waveform as an effective modality for identifying ischemia via video alone, as it enhanced performance for inexperienced evaluators. EVM+waveform is effective for assessing various skin types, especially those with higher skin melanin content.

Type of study/level of evidence: Diagnostic, IV.

Rapid and accurate identification of limb ischemia is crucial for appropriate trauma triage and treatment.[1,2] Advanced treatments, such as revascularization and replantation, are only available at certain centers that are often far from the site of injury, adding additional burden to the clinical assessment and transfer decision.[3–5] However, the accuracy of clinical evaluation for ischemia varies depending on examiner experience, appearance of the limb, lighting, skin type, and skin pigmentation, among other factors.[6,7] As a result, many urgent transfers are made unnecessarily.[8–10] Although several modalities have been used to try and improve the examination of limb or digit perfusion, each has its limitations, and many are susceptible to variations in skin pigmentation.[11–15]

Eulerian video magnification (EVM) is a spatiotemporal decomposition algorithm that can amplify subtle signals when

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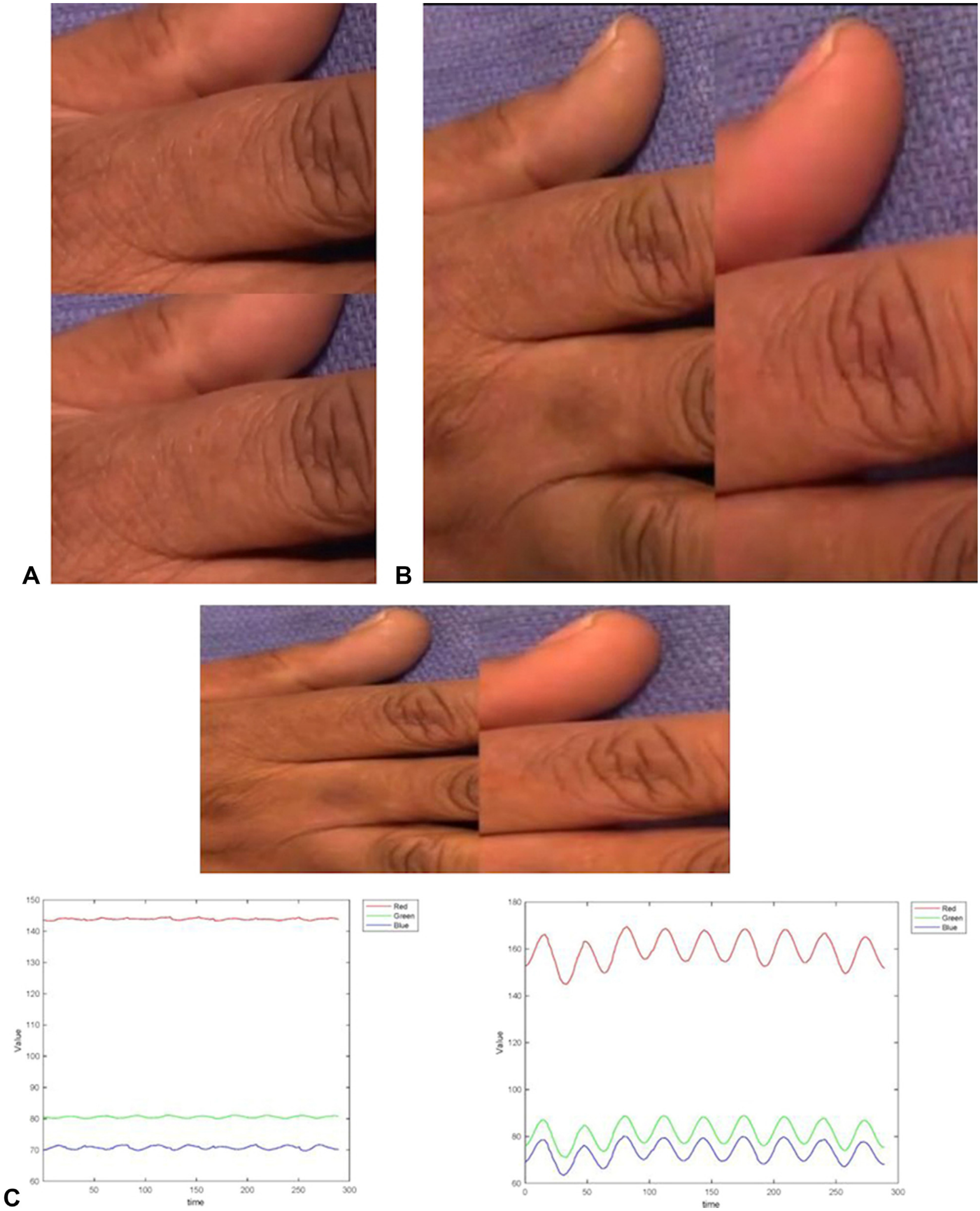

Figure 1. **A** Ischemic hand. **B** Perfused hand. **C** Corresponding EVM processing combined with waveform output video image.

applied to conventional video. This can be used to augment the colors within the video so they are visibly clearer; notably, red pigment can be enhanced enough that pulsations in tissue can be detected via video. Our team has taken this open-source technology, enhanced it to improve robustness for varying skin pigment types, and added a waveform processing component that corresponds to the changes in color detected in the video. In other words, if pulsatile colors are detected, a waveform that represents these changes is created. If no pulsatile coloration is picked up, the waveform is flat (Fig. 1A-C). We believed that this could enhance

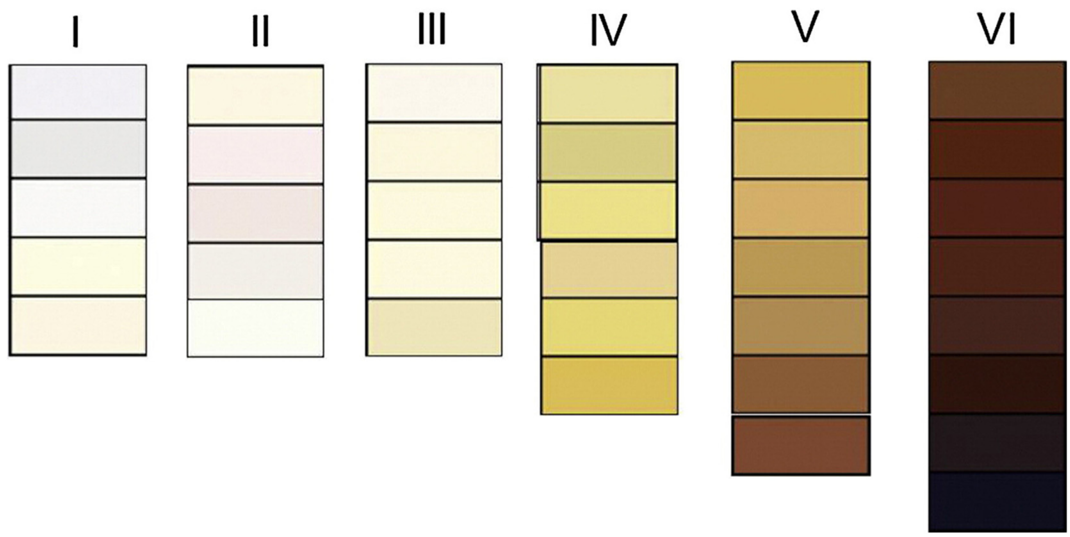

Figure 2. Comparison of skin color classification by von Luschan schema and Fitzpatrick scale.

tele-triage via video, as that technology has had mixed success thus far.[16]

In prior work, we showed that this EVM+waveform technology provided enhanced visualization of hands and fingers via video such that hand surgeons and hand surgery trainees were more successful in differentiating perfusion from ischemia via video across different skin types.[17] To expand on these data, we were interested in how less experienced people would be able to use EVM+waveform processing of videos to evaluate hand and finger perfusion. This would provide the use case for in-field first responders with less hand trauma experience to use EVM+waveform video evaluation. As such, this study aims to assess the efficacy of the EVM+waveform technology for aiding the identification of hand ischemia when the evaluators have little or no experience with hand injuries. We hypothesized that EVM+waveform would enhance evaluator performance and improve accuracy in determining whether a hand/finger is ischemic or perfused via video, regardless of skin pigment type.

Methods and Materials

The design of this study was similar to our initial study; additional details are available in that publication.[17]

Volunteer recruitment for obtaining videos

After obtaining Institutional Review Board approval, 12 healthy volunteers were recruited to undergo cyclic tourniquet-induced upper extremity ischemia while the hand was recorded on video. Participants were recruited through email, posters, online, and word of mouth. We included participants who were healthy volunteers between the ages of 18–60 years. We excluded those with a history of any of the following: coronary artery disease, cardiac disease, hypertension, peripheral vascular disease, Raynaud syndrome, vascular surgery to the upper extremity, neurologic condition of the upper extremity, personal history of sickle cell anemia, thalassemia, upper extremity trauma requiring revascularization, cerebral vascular accident or transient ischemic attack, or chronic pain syndrome. Demographic information and medical history were recorded along with a 10-item Fitzpatrick Skin Type (FP) questionnaire.[18,19] The skin color of each subject was further evaluated using the Felix von Luschan color scale (vL). These vL ratings were converted and compared with the FP classification scale to assign each subject to one of the FP skin phenotypes (I–VI) (Figs. 2 and 3).[20,21]

Processing technology

EVM is an open-source application developed by the Massachusetts Institute of Technology Computer Science & Artificial Intelligence Lab. This software algorithmically enhances video giving a new output video that displays the original video with an overlaid visualization of amplified color fluctuations that correspond to blood flow frequencies. However, EVM is sensitive to noise, making it susceptible to video instability or slight movements of the subject. It also is less successful in amplifying weak signals in videos of individuals with higher levels of skin melanin. To overcome these limitations, we developed an additional component, an algorithm that calculates the average pixel values for each frame on the Red, Green, Blue Scale. This approach allows us to extract the color characteristics from the EVM-processed video that we then use to make distinct waveforms for each of the three-color channels. These serve as a measurement of the signal intensity in each color channel over time and are used to enhance the visualization of changes in signal intensity originating from alterations in peripheral blood flow (Fig. 1 A–C). This EVM+waveform processing approach was evaluated in our initial manuscript on this topic.[17] We have made no changes to the processing algorithm between that manuscript and this one.

Video acquisition

An 18-inch tourniquet was applied to each volunteer's randomly chosen upper limb and positioned over two layers of cast padding. The arm was placed on a table and filmed. Following 3 minutes of recording the perfused state, the tourniquet was inflated to 250 mm Hg and cessation of perfusion was confirmed using two methods. The first was a pulse oximeter placed on the index finger and removed once there was no longer a reading (complete ischemia); the second was a Doppler examination of the radial and ulnar arteries to confirm no audible flow.

Videos were cut into 10-second clips of perfusion and ischemia. Each 10-second clip was chosen based on minimal

Fitzpatrick Type	Description	Effect of Light Exposure	Von Luschan's Schema
I	Pale, fair, freckles	Always burns, never tans	Very light
II	Fair	Usually burns, sometimes tans	Light
III	Light brown	May burn, usually tans	Intermediate
IV	Olive brown	Rarely burns, always tans	Mediterranean
V	Brown	Moderate constitutional pigmentation	Dark or brown
VI	Black	Marked constitutional pigmentation	Very dark or black

Figure 3. Fitzpatrick skin type and von Luschan schema skin color classification based on description and effect of light exposure.

variation in movement, lighting, and positioning. The skin types used included numbers three through six on the Fitzpatrick scale; we did not include types one and two as those tend to be easiest to evaluate for perfusion and we wanted to test more challenging clinical scenarios. We then made two versions of each video, including unprocessed and processed with EVM+waveform. These clips were then entered into a 26-question web-based survey through Microsoft Forms. There were two question formats presented in each survey. The first format provided the survey respondent with a video clip that was processed with the EVM+waveform technology. After watching the clip, the respondent had to determine if the hand in the video they just watched was ischemic, perfused, or if they were uncertain about the hand's perfusion status. We allowed for an "unsure" answer to avoid random guessing that could artificially inflate (or diminish) performance results. The second question format included in the survey was a side-by-side of two videos, both were either processed with EVM+waveform or both were unprocessed. Both videos were clips of the same patient, with one of the videos demonstrating the hand during an ischemic state and the other video demonstrating the hand during a perfused state. The respondent was told that one of the frames had an ischemic limb, and they were instructed to select which video was demonstrating ischemia. The objective of this question format is to simulate a scenario where one finger is injured but the neighboring finger could serve as a visual "control". The positioning of the ischemic video (left or right) was varied at random for each question. Each survey respondent had both processed side-by-side comparison questions and unprocessed side-by-side comparison questions. Each video used in the survey was able to be replayed at the discretion of the survey respondent with no limit to the number of replays allowed.

Volunteer recruitment for survey evaluation

To distribute the survey, we used the social media platforms Instagram, Twitter, and LinkedIn. This distribution technique allowed the survey to reach individuals with little to no medical experience. A total of five respondents were randomly chosen and given $100 Visa gift cards as an incentive for the individual to complete the study. The responses were screened and filtered for scammers to maintain the validity of the study. None of the survey respondents had prior training with/or exposure to the software nor were they presented with any education on the visual differences between ischemic and perfused hands.

Table
Demographic Characteristics of All Respondents

Total Participants	64
Sex	
Female	36
Male	28
Race	
White	36
Black or African American	12
Asian	11
Other/unspecified	5
Ethnicity	
Hispanic/Latinx	8
Not Hispanic/Latinx	47
Not Specified	9
Highest level of education	
Bachelor's degree	20
Doctoral degree (PhD, DDS, DBA, EdD, MD, DO, Pharm D, PsyD, and JD)	20
Master's degree	17
Some college	6
High school diploma	1
Do you work in health care?	
Yes	44
No	20

Analysis

Descriptive statistics were used to report respondent demographic characteristics. All questionnaire response data were collected and analyzed blindly. The "Unsure" responses that were recorded were considered as "Incorrect" in the analyses. The data were stratified using three variables: the health care experience of the respondent, whether the respondent had a medical doctorate (MD) or equivalent degree, and the skin type of the hand in the video. Each of the three variables was assessed using the number of correct responses as a percentage of the total questions. The accuracy percentages of the control (unprocessed) and of the experimental (EVM+waveform) were compared using a t test for each variable.

	Unprocessed % (n=14)	Processed % (n=12)	p-value
Healthcare Experience	0.52	0.70	0.01
No Experience	0.36	0.63	< 0.001

Figure 4. Comparison of the percentage of correct responses between respondents with health care experience and respondents without health care experience based on EVM+waveform processing status.

	Unprocessed % (n=14)	Processed % (n=12)	p-value
MD	0.55	0.89	< 0.001
No MD	0.44	0.61	0.003

Figure 5. Comparison of the percentage of correct responses between md respondents and non-md respondents based on EVM+waveform processing status.

Results

We received 64 completed and legitimate survey responses. Participants' biographical information is summarized in the Table. There were 36 women and 28 men survey takers. The respondents had various levels of highest education attained, including one with a high school degree, six with some college education, 20 with bachelor's degrees, 17 with master's degrees, and 20 with doctoral degrees. Out of 64 survey takers, 44 work in health care; none had any specialty or field overlap with hand surgery or vascular surgery. A list of occupations for each of the survey takers who work in health care and categorize the number of years spent working in health care into less than five ($n = 21$), five to ten ($n = 13$), and more than ten ($n = 10$) is provided in Appendix 1 (available on the *Journal*'s website at www.jhsgo.org). We divided all residents by their level of training into PGY1−2 ($n = 9$) and PGY 3−4 ($n = 2$). The five attending physicians included in the study have practiced for 6 years on average.

The accuracy of the EVM+waveform responses was compared to the accuracy of the control (unprocessed video) group responses. The EVM+waveform videos were rated with significantly greater accuracy regardless of the respondent's health care experience. Respondents with health care experience were 52% accurate without using the EVM+waveform technology, whereas the responses were 70% accurate when using the EVM+waveform technology ($P < .05$). The respondents without health care experience were 36% accurate without processing and 63% accurate with processing ($P < .05$). These data are further detailed in Figure 4.

Health care experience was further evaluated by assessing the accuracy of the MD respondents compared to all the other respondents in the study. As anticipated, the MD group had a higher accuracy percentage than the non-MD group when evaluating either processed or unprocessed video. Both the MD and non-MD groups had a statistically significant and clinically meaningful improvement in determining ischemia when using the EVM+waveform technology. These data are in Figure 5.

We also evaluated the effects of skin pigmentation on the accuracy of the responses based on MD status. The improvements in accuracy when using EVM+waveform in the MD group reached statistical significance when assessing hands of FP types III, V, and VI ($P < .05$; Figure 6). Accuracy scores when evaluating FP type IV hands did not significantly improve ($P = .08$), but the improvement in this group is clinically meaningful. Within the MD cohort, accuracy scores in the unprocessed videos are negatively correlated with Fitzpatrick classes as expected. Conversely, the accuracy scores are not largely impacted by skin type when using the EVM+waveform technology. The two highest accuracy percentages (both 93%) were when the software was used to evaluate hands with FP III and FP VI classifications (Fig. 6).

Figure 6 also presents the same analysis performed in the non-MD cohort. The improvements in accuracy were statistically significant at FP types IV, V, and VI. The improvements when assessing hands with FP III classification were not statistically significant and the impact was meaningful but not to the extent of the other groups. Just as in the MD cohort, the accuracy of the unprocessed videos had an inverse relationship with skin type, but in the processed group the Fitzpatrick classification did not affect the accuracy scores. These data are further detailed in Figure 6.

Out of 2,560 questions completed, there were 408 "unsure" answers. They were all considered incorrect answers, likely overestimating the true number of incorrect answers. This overestimate increases the validity of these findings and demonstrates the effectiveness of the EVM+waveform technology.

Discussion

This is a follow-up study testing how our EVM+waveform video processing technology can improve accuracy in determining finger/hand ischemia when being used by people of various backgrounds but with limited hand surgery exposure. Considering the data presented, the EVM+waveform technology supports significant improvements in assessing perfusion and is consistent regardless of medical experience and regardless of the skin pigmentation of the patient being assessed.

The EVM+waveform technology supported significantly better performance in determining ischemia regardless of the evaluator's experience. There was a statistically significant improvement in both the cohort with health care experience and the cohort without health care experience when using the EVM+waveform processing technology. Similar trends were evident when comparing responses from MD versus non-MD participants. Although both groups showed significant improvements with the use of the EVM+waveform technology, the improvements were greater in the non-MD cohort because their performance with unprocessed video was notably worse. It is evident that this technology can improve a physician's ability to evaluate ischemia, but it is also essential to highlight the potential role this technology can play in allowing professionals of varying backgrounds to assess limb perfusion status accurately and effectively.

Skin pigmentation directly affects a clinician's ability to evaluate perfusion.[6] This trend was evident in our control data. When using the EVM+waveform technology, the data showed no relationship between the accuracy of ischemia evaluation and skin type. This was also seen in our prior study and is a primary reason EVM+waveform technology has such potential to excel where current modalities lack.

Although the data show promise, this technology is still in the early stages of research and development. Even with the technology no evaluator had a perfect performance. Moreover, the non-MD group did show a significant improvement with the use of EVM+waveform but there was still a low overall accuracy in the non-MD group. It is important to note that the respondents using the EVM+waveform technology were not trained with or instructed on this software prior to using it. The accuracy ratings would likely improve with training of some sort; therefore, it is possible that the clinical application of this product would outperform these preliminary data.

Once established, this technology could fill gaps within the current standard of ischemia identification in the distal upper extremity. The current care standards and related options, including

	No MD (n=49)			MD (n=15)		
Fitzpatrick Type	Unprocessed	Processed	p-value	Unprocessed	Processed	p-value
III	0.51	0.59	0.11	0.62	0.93	0.01
IV	0.44	0.61	0.05	0.67	0.87	0.08
V	0.43	0.60	< 0.001	0.51	0.87	< 0.001
VI	0.37	0.65	< 0.001	0.40	0.93	< 0.001

Figure 6. Comparison of the percentage of correct responses in the MD cohort and the non-MD cohort based on processing status across videos of varying skin types.

bedside Doppler, photo plethysmography, near-infrared spectrometry, and pulse oximetry, all have weaknesses in accuracy, usability, and/or accessibility. Bedside Doppler is often the preferred method for evaluating perfusion, but its effectiveness varies, especially among inexperienced providers. This is because it is reliant on operator skill, and the reading can often be affected by vasospasm/vasoconstriction. Duplex ultrasound is another commonly used method, but its utility is also limited by provider experience and equipment requirements.[22] Pulse oximetry is another common technique, but it is influenced by melanin concentration and can overestimate arterial oxygen saturation in hypoxia among individuals with darker skin.[23–25] Furthermore, direct skin contact is necessary for pulse oximeters, which limits their application in trauma care. Near-infrared spectroscopy is used to monitor flaps but may be impacted by skin melanin, especially when being used as a spot check device.[26] Moreover, this technology lacks in accessibility, logistics, and cost, and there are no well-defined parameters to direct intervention based on tissue oxygenation readings.[27] Another technique for evaluating perfusion is photoplethysmography, which provides information on changes in the local blood volume over time. Although this method can be effective, it is also influenced by melanin content and device placement with pressure.[28]

In addition to the clinical benefits of the EVM+waveform technology, there are also health care system improvements that this technology can provide. This technology's remote usability will allow for telemedicine and resource management improvements. Some high-volume trauma centers use tele-triage to maximize efficiency and to reduce the high volume; however, they still deal with many unnecessary trauma transfers.[29] Technologies such as EVM+waveform will help expand the abilities of such platforms. The usability of this technology allows for accurate assessments to be made by professionals with less training and would stand to improve workflow in busy health systems.

Although all of this is encouraging, this study has inherent weaknesses. One weakness is the number of survey participants. The percentages show improvement across groups; however, larger sample sizes would add to the robustness of our results. Another weakness of the study was the administration of the survey and the survey respondent cohort. The respondents were limited to those who were active on social media platforms such as Instagram, LinkedIn, and Twitter. Moreover, the respondents were those in the social circles of the study's administrators or research team members so even if the respondents did not have personal medical experience, it is possible this recruitment approach limited the random nature of the responses. Given this recruitment strategy, the potential pool of respondents along with the independence between each of the respondents is uncertain. Additionally, the evaluator watching the videos was not trained in the software prior to the evaluation. Prior training or familiarity with the technology could improve the accuracy of the responses. Lastly, the videos within the survey did not include the entire hand, some had only a side-by-side comparison with a single digit within a frame, which could have potentially changed the evaluator's answers and made it more difficult.

Identifying distal upper extremity ischemia is difficult and highly variable. These difficulties are exacerbated in the remote setting and can be detrimental for triage and decision-making in the ED. Darker skin pigmentation exacerbates these difficulties. The EVM+waveform technology shows high efficacy in determining ischemia in the remote setting via video. More specifically, the data show an independent relationship between the accuracy of ischemia evaluation and melanin concentration. The benefits that come with using the EVM+waveform technology hold up regardless of the evaluator experience, increasing the potential applicability of this technology. These preliminary results indicate the possibility of an effective perfusion assessment tool that has the potential to be noncontact, low cost, rapid, and accessible and can be widely used in the field and via tele-triage.

Conflicts of Interest

The study was funded by AFSH clinical research grant #2819. No benefits in any form have been received or will be received related directly to this article.

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