

Original Research Article

Retinal Vascular Biometrics for Forensic Personal Identification: A Pilot Validation Study in Palembang, Indonesia

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ABSTRACT

Background. Identification of the dead after mass-fatality events can fail when friction ridges are destroyed, dental records are missing or DNA is degraded. The retinal vascular pattern is protected and individually distinctive, but local feasibility data are scarce.

Objective. To evaluate the feasibility and preliminary discriminative performance of a non-mydratic fundus imaging and vessel-matching pipeline in adults in Palembang, Indonesia.

Methods. In this prospective cross-sectional pilot validation study, one right-eye fundus image was acquired from each of 100 adult volunteers (aged 20–65 years; 52 men, 48 women). Vessels were segmented with Gaussian matched filters, skeletonized and summarized as a five-feature vector; a fused score combined correlation and feature distance. Reference comparisons were 100 self-matches and impostor comparisons numbered 9,900. Age groups were compared by analysis of variance.

Results. Extraction plus matching took 1.50 s per comparison (1.76 s with pre-processing). Recomputed from the tabulated scores, 21% of self-matches scored below 0.80 and 16% of impostor comparisons above it; error rates crossed at about 18.5%, the area under the ROC curve was about 0.89 and d' was 2.55. Self-match scores did not differ significantly among age groups ($F = 0.962$, $p = 0.386$; $n = 25$ –40 per group).

Conclusion. The pipeline was feasible and fast, but discrimination was moderate, and self-matched reference trials, one image per person and no postmortem data cannot support claims of identification accuracy or age invariance. Independent repeat captures and cadaveric validation are needed.

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1. Introduction

Reliable identification of the dead supports death certification, criminal and civil proceedings and the return of remains to families.^{1,2} In mass-fatality events, disaster victim identification (DVI) relies mainly on friction ridges, dental comparison and DNA.^{2,3}

Each of these identifiers has limits. Friction ridges need preserved skin, which may be lost through burning, immersion or decomposition.^{3,4} Dental comparison needs antemortem dental records, which can be incomplete in resource-limited settings.⁵ DNA profiling is powerful but slower and costlier, and it needs reference samples from relatives or personal effects.^{6,7} Complementary, rapid and non-invasive identifiers are therefore of practical interest.

The retina lies within the orbit, and its vascular pattern has long been proposed as an individual identifier, including between monozygotic twins.^{8,9} Automated retinal identification systems based on vessel landmarks, correlation and related descriptors have been described for almost two decades.^{10–13} Non-mydratic fundus

cameras allow non-contact imaging without pupil dilation in living people. After death, ophthalmic examination has been used in forensic practice, although corneal clouding and changes in the retinal blood columns limit it.^{14–17}

Data on retinal vessel matching in Indonesian adults are limited, and ocular pigmentation, fundus reflectivity and disease prevalence may alter segmentation and thresholds. Indonesia is exposed to earthquakes, volcanic eruptions, tsunamis and transport accidents, which makes additional identifiers relevant to DVI. The objective of this study was to evaluate, in a pilot sample of 100 adults in Palembang, the feasibility, computational cost and preliminary discriminative performance of a non-mydratic retinal vessel-matching pipeline, and to compare its scores across age groups.

2. Methods

2.1. Study design and setting

This was a prospective cross-sectional pilot validation study in Palembang, South Sumatra, with recruitment between August and December 2023. Biometric testing

was designed with reference to ISO/IEC 19795-1;¹⁸ full conformity is not claimed because the design has a single capture per person.

2.2. Participants

A convenience sample of 100 adults aged 20–65 years was recruited through community outreach and the outpatient ophthalmology clinics associated with Dr. Mohammad Hoesin General Hospital, Palembang. Inclusion criteria were clear ocular media sufficient for non-mydratic imaging and verified identity documents. Exclusion criteria were dense media opacity (mature cataract or dense corneal scarring), active vitreous hemorrhage, extensive retinal detachment, severe congenital coloboma and inability to fixate.

2.3. Image acquisition

Images were acquired by trained ophthalmic technicians with a non-mydratic fundus camera (Topcon TRC-NW400, Topcon Corporation, Tokyo, Japan) under standardized room illumination. One uncompressed color image (2560×1920 pixels, 24-bit RGB) of the right eye, centered between the optic disc and the fovea at a 45° field, was taken from each participant after two minutes of dark adaptation, with a natural pupil diameter of at least 3.5 mm. No mydratic was used.

2.4. Pre-processing and feature extraction

Images were cropped to the retinal aperture and downsampled by bilinear interpolation to 512×512 pixels. The green channel was extracted, enhanced by contrast-limited adaptive histogram equalization (CLAHE; 8×8 tiles, clip limit 2.0)¹⁹ and smoothed with a 3×3 median filter. Vessels were segmented with a bank of two-dimensional Gaussian matched filters^{20,21} using the kernel $G(x, y) = -\exp(-x^2/2\sigma^2)$ for $|y| \leq L/2$ at twelve orientations (0° to 165° in 15° steps), and the maximum response per pixel was kept. The response map was binarized by local thresholding, components smaller than 30 pixels were removed and the mask was closed morphologically. The mask was thinned with the Zhang–Suen algorithm,²² and skeleton pixels with three vessel neighbors in a 3×3 window were counted as bifurcations and those with four as crossovers.

The fractal dimension (D_f) was estimated by box counting²³ with box sizes $\epsilon = 4, 8, 16, 32, 64$ and 128 pixels, as the slope of $\log N(\epsilon)$ against $\log(1/\epsilon)$. The five-element feature vector comprised D_f , vessel density (vessel pixels as a fraction of the circular retinal area), the number of bifurcations, the number of crossovers and mean vessel caliber. Analyses used Python 3.11 with OpenCV 4.9.0, scikit-image 0.22.0²⁴ and NumPy.²⁵

2.5. Matching score and comparison design

For two images A and B, spatial similarity was the normalized cross-correlation (NCC) of the binary vessel masks, $NCC = \Sigma[(A - \mu_A)(B - \mu_B)] / \sqrt{\Sigma(A - \mu_A)^2 \Sigma(B - \mu_B)^2}$, which ranges from -1 to 1. The Euclidean distance d_E between standardized feature vectors was converted to $1/(1 + d_E)$. The combined score was $S = w \cdot NCC + (1 - w) \cdot [1/(1 + d_E)]$, with $w = 0.60$.

Only one image was acquired per participant. Reference (“genuine”) trials were therefore formed by pairing each image with itself (100 self-matches), and impostor trials by comparing each image with all 99 others (9,900 ordered pairs, equal to 4,950 unique pairs because scores are symmetric). A self-match gives $NCC = 1$ and $d_E = 0$, and so does not measure whether the same eye is recognized on a second capture.

2.6. Performance measures and statistical analysis

The false acceptance rate (FAR) is the proportion of impostor comparisons scoring above the threshold θ , and the false rejection rate (FRR) is the proportion of reference comparisons scoring at or below θ . The equal error rate (EER) is the rate at which they are equal. Decidability was $d' = |\mu_{ref} - \mu_{imp}| / \sqrt{[0.5(\sigma_{ref}^2 + \sigma_{imp}^2)]}$, and the area under the ROC curve (AUC) was computed with ties within a score bin counted as half. Because raw scores were not available to this revision, operating points, AUC and the crossover were recomputed from the binned counts in Table 3. Wilson 95% confidence intervals are given for FRR; a participant-level resampling interval is needed for FAR. Self-match scores were compared among three age groups (20–35, 36–50 and 51–65 years) by one-way analysis of variance (ANOVA) and permutation tests at a two-sided α of 0.05.

2.7. Ethical approval and data protection

The study followed the Declaration of Helsinki^{26,27} and was approved by an institutional ethics committee (details in the Declarations). Written informed consent was obtained from every participant.

3. Results

3.1. Participants

All 100 volunteers yielded fundus images of acceptable quality without pharmacological mydriasis. The 52 men and 48 women had a mean age of 42.5 ± 12.3 years (range 20–65): 35 were aged 20–35, 40 were aged 36–50 and 25 were aged 51–65 years. 78 participants were Malay, 12 Javanese, 6 Chinese Indonesian and 4 of other ethnic groups. Twenty-eight (28.0%) had an ocular history (mainly refractive error), 8 had diabetes and 15 hypertension, and 30 were current smokers (Table 1, Figure 1).

Table 1. Characteristics of the 100 participants.

Characteristic	Category	n	%
Age, years	Mean ± SD (range)	42.5 ± 12.3 (20–65)	
	20–35	35	35.0
	36–50	40	40.0
	51–65	25	25.0
Sex	Male	52	52.0
	Female	48	48.0
Ethnicity	Malay	78	78.0
	Javanese	12	12.0
	Chinese Indonesian	6	6.0
	Other (Batak, Minangkabau, Sundanese)	4	4.0
Education	Junior high school or lower	15	15.0
	Senior high school	45	45.0
	Diploma	20	20.0
	Bachelor’s degree or higher	20	20.0
Employment	Private sector employee	35	35.0
	Civil servant	25	25.0
	Self-employed	20	20.0
	Not working	10	10.0
	Retired	10	10.0
Ocular history	Any eye condition	28	28.0
	Refractive error	25	25.0
	Early cataract (grade I/II)	2	2.0
	Pterygium	1	1.0
	No eye condition	72	72.0
Corrective lenses	Spectacles or contact lenses	22	22.0
Systemic disease	Diabetes mellitus	8	8.0
	Hypertension	15	15.0
Smoking	Current	30	30.0
	Former	15	15.0
	Never	55	55.0

Notes: SD, standard deviation. Age interquartile range, 31–53 years. Hypertension is defined as systolic blood pressure ≥ 140 mmHg or antihypertensive treatment.

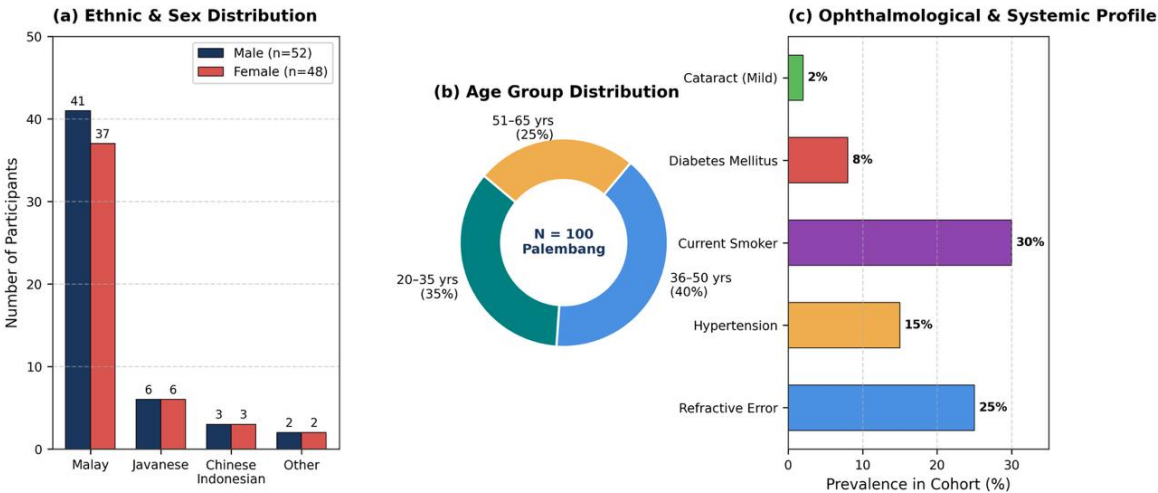


Figure 1. Ethnic and sex distribution (a), age-group distribution (b) and ocular and systemic profile (c) of the cohort (N = 100). Panel (a) shows male/female counts per ethnic group (Malay 41/37, Javanese 6/6, Chinese Indonesian 3/3, other 2/2).

3.2. Vessel features

Feature metrics are summarized in Table 2 and the processing steps are illustrated in Figure 2. The mean fractal dimension was 1.452 ± 0.038 , vessel density 11.84

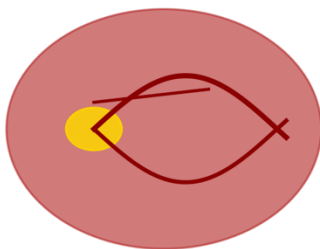
$\pm 1.62\%$, bifurcations 84.6 ± 14.2 and crossovers 14.2 ± 4.5 per image, and mean caliber 6.84 ± 0.82 pixels. After CLAHE and median filtering the vessel contrast ratio was 0.684 ± 0.072 and the signal-to-noise ratio 24.6 ± 2.8 dB; no before-and-after comparison was made.

Table 2. Vessel-feature and image-quality metrics (N = 100).

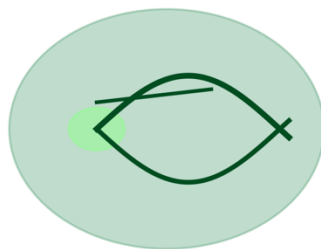
Metric	Definition	Mean $\pm$ SD	Median (IQR)	95% CI
Fractal dimension (Df)	Slope of $\log N(\epsilon)$ vs $\log(1/\epsilon)$	1.452 ± 0.038	1.450 (1.425–1.478)	1.444–1.460
Vessel density, %	Vessel pixels / retinal area	11.84 ± 1.62	11.75 (10.60–12.95)	11.52–12.16
Bifurcations, count	Skeleton pixels with 3 neighbors	84.6 ± 14.2	83.0 (74.0–94.0)	81.8–87.4
Crossovers, count	Skeleton pixels with 4 neighbors	14.2 ± 4.5	14.0 (11.0–17.0)	13.3–15.1
Mean caliber, pixels	Mean vessel width	6.84 ± 0.82	6.80 (6.25–7.35)	6.68–7.00
Optic disc diameter, pixels	Major axis	92.4 ± 8.6	91.5 (86.0–98.0)	90.7–94.1
Vessel contrast ratio	$(I_{bg} - I_v) / (I_{bg} + I_v)$	0.684 ± 0.072	0.680 (0.635–0.730)	0.670–0.698
Signal-to-noise ratio, dB	$10 \log_{10} (P \text{ signal} / P \text{ noise})$	24.6 ± 2.8	24.5 (22.5–26.5)	24.0–25.2

Notes: CI, confidence interval; IQR, interquartile range; SD, standard deviation; I_{bg} , background intensity; I_v , vessel intensity. Images were resized from 2560×1920 to 512×512 pixels before filtering.

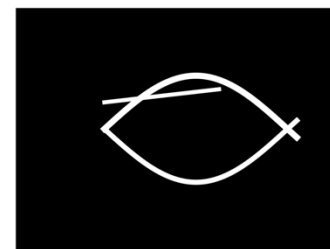
(a) Raw Non-Mydriatic Fundus (RGB 2560×1920)



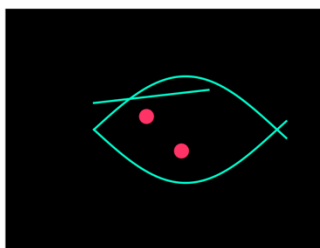
(b) Green Channel + CLAHE Enhanced Contrast (512×512)



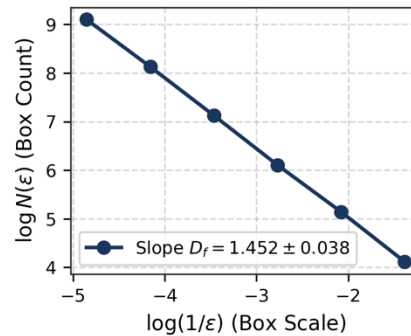
(c) 2D Gaussian Filter Segmentation Binary Mask



(d) Vessel Skeleton & Minutiae (Bifurcations • & Crossings)



(e) Fractal Dimension (D_f) Box-Counting Scaling



(f) Integrated Biometric Vector Salient Descriptors

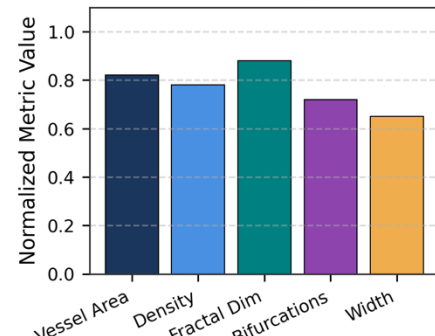


Figure 2. Schematic illustration of the processing pipeline: (a) raw fundus image; (b) green channel after CLAHE; (c) binary vessel mask; (d) skeleton with bifurcation and crossover points; (e) box-counting plot; (f) normalized feature vector. Panels (a)–(d) are schematic drawings, not study images.

3.3. Score distributions and error rates

Score distributions are given in Table 3 and Figure 3a. Self-match scores ranged from 0.35 to 1.74 (mean 1.05 ± 0.25) and impostor scores from 0.04 to 1.52 (mean 0.45 ± 0.22). Exactly 79.0% of self-match scores exceeded 0.80, whereas 21 (21.0%; 95% CI 14.2–30.0%) were at or below it. One self-match (1.0%) fell in the 0.21–0.40 bin and may be related to an older participant with mild grade II cataract; no image-quality data support this attribution. Of the impostor comparisons, 70.0% scored below 0.60, and

5.0%, 2.0% and 1.0% fell in the 1.01–1.20, 1.21–1.40 and 1.41–1.60 bins; none exceeded 1.60.

The two distributions overlap substantially (Table 3, Figure 3a). At $\theta = 0.80$ the FRR was 21.0% and the FAR 16.0%; FRR and FAR crossed at θ of about 0.77 at roughly 18.5% by linear interpolation. The AUC was about 0.89 (0.88 using the tabulated total of 9,999), d' was 2.55, and the ratio of the proportions scoring above 1.00 (49% of self-matches, 8% of impostor comparisons) was about 6 (Figure 3b).

Table 3. Self-match and impostor score distributions with operating points derived from the bin counts.

Score bin (S)	Self-match, n	Self-match, %	Impostor, n	Impostor, %	θ (upper limit)	FRR, %	FAR, %
0.00–0.20	0	0.0	1,584	16.00	0.20	0	85.0
0.21–0.40	1	1.0	2,871	29.00	0.40	1	56.0
0.41–0.60	5	5.0	2,475	25.00	0.60	6	31.0
0.61–0.80	15	15.0	1,485	15.00	0.80	21	16.0
0.81–1.00	30	30.0	792	8.00	1.00	51	8.0
1.01–1.20	25	25.0	495	5.00	1.20	76	3.0
1.21–1.40	15	15.0	198	2.00	1.40	91	1.0
1.41–1.60	7	7.0	99	1.00	1.60	98	0.0
1.61–1.80	2	2.0	0	0.00	1.80	100	0.0
1.81–2.00	0	0.0	0	0.00	2.00	100	0.0
Total	100	100.0	9,999	101.00			

Notes: FAR, false acceptance rate (impostor comparisons above θ , as a percentage of 9,900); FRR, false rejection rate (self-match comparisons at or below θ); S, combined matching score. Self-matches pair each image with itself ($n = 100$); impostor comparisons are 9,900 ordered pairs.

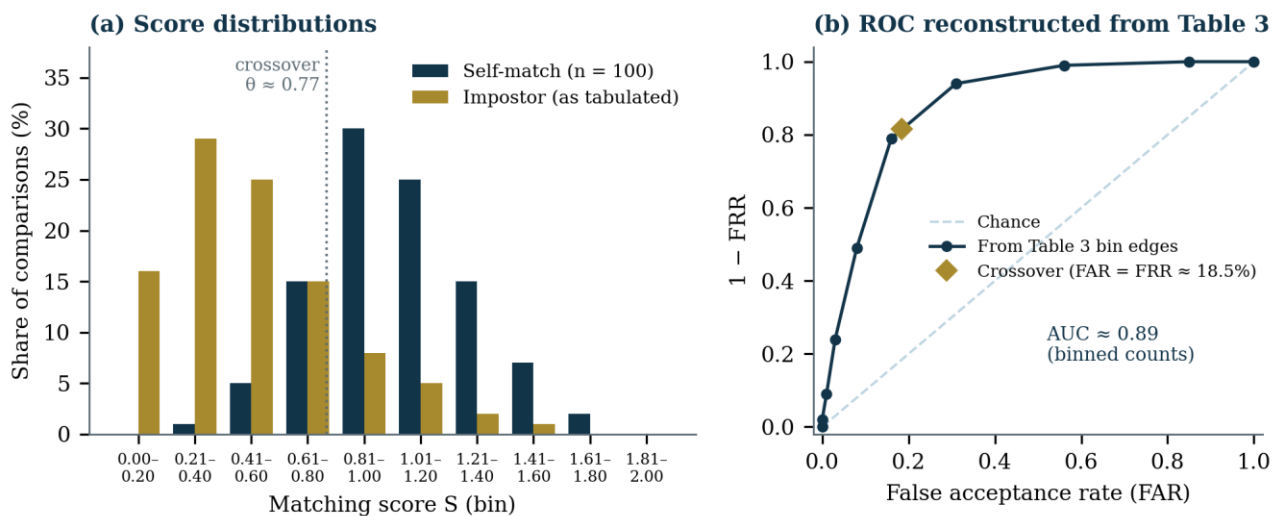


Figure 3. Score distributions and receiver operating characteristic (ROC) curve reconstructed from the bin counts in Table 3. (a) Share of self-match and impostor comparisons per score bin (impostor percentages as tabulated, total 101%); (b) ROC points at the bin edges, with the FAR = FRR crossover (about 18.5%). The curve is redrawn from Table 3, not from raw scores.

3.4. Computation time

Stage times are shown in Table 4 and Figure 4. Pre-processing took 0.26 ± 0.04 s, feature extraction 0.80 ± 0.10 s and matching 0.70 ± 0.08 s, so one comparison took 1.50 ± 0.12 s for extraction plus matching and about 1.76 s

including pre-processing. Exhaustive search of a 99-record gallery would take $99 \times 0.70 = 69.3$ s. A two-tier search that pre-filters by feature distance (0.10 s per record) and then correlates the top five candidates would take about 13.4 s, a reduction of 80.7%.

Table 4. Processing time per pipeline stage.

Stage	Mean, s	SD, s	Components (mean, s)
Image acquisition (per participant)	2.50	0.50	Non-contact capture
Pre-processing (per image)	0.26	0.04	Resizing 0.05; CLAHE 0.12; median filter 0.08; green-channel split 0.01
Feature extraction (per image)	0.80	0.10	Vessel segmentation 0.45; geometry and minutiae 0.20; fractal analysis 0.15
Matching (per comparison)	0.70	0.08	NCC 0.50; Euclidean distance 0.10; score fusion 0.10
Extraction + matching	1.50	0.12	Cycle as reported in the submission
Pre-processing + extraction + matching	1.76	n/r	Sum of stage means; SDs are not additive
Exhaustive 1:99 search	69.3	n/r	99×0.70 s
Two-tier 1:99 search	13.4	n/r	99×0.10 s + 5×0.70 s

Notes: CLAHE, contrast-limited adaptive histogram equalization; n/r, not reported; NCC, normalized cross-correlation; SD, standard deviation. Single-threaded Python on an Apple Silicon workstation.

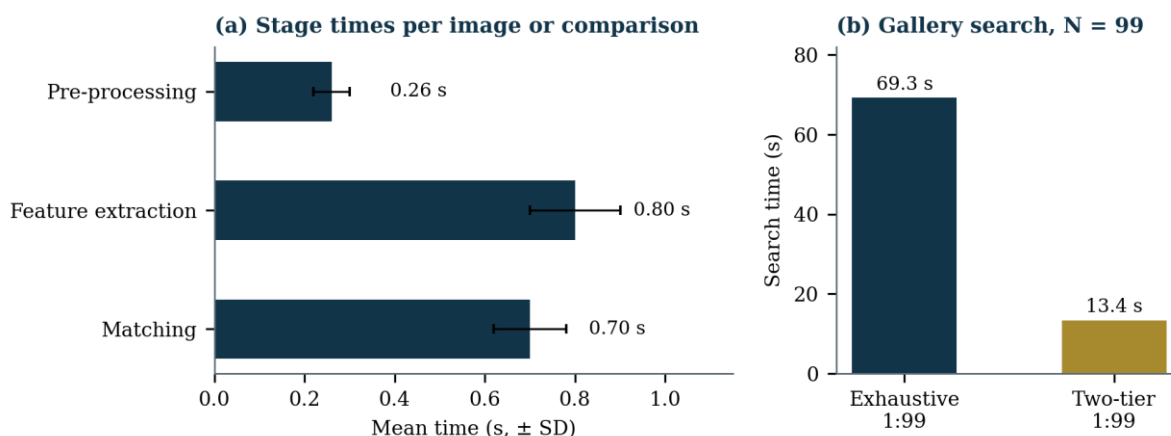


Figure 4. Processing time. (a) Mean time ($\pm$ SD) of pre-processing, feature extraction and matching; (b) search time for a 99-record gallery, exhaustive versus two-tier (feature-distance pre-filter, then correlation of the top five). Redrawn from Table 4; times for larger galleries were not measured.

3.5. Age groups

The groups of 35, 40 and 25 participants contributed 595, 780 and 300 within-group and 1,400, 875 and 1,000 between-group impostor pairs, 4,950 unique pairs in all

(Table 5). Self-match score means did not differ significantly among the three age groups (one-way ANOVA, $F = 0.962$, $df = 2$ and 97 , $p = 0.386$), and pairwise permutation tests gave $p > 0.05$. With 25–40 participants per group this finding cannot show equivalence.

Table 5. Participants and impostor pairs by age stratum.

Stratum	Group 1, n	Group 2, n	Impostor pairs, n
Within group	20–35 y (35)	20–35 y	595
Within group	36–50 y (40)	36–50 y	780
Within group	51–65 y (25)	51–65 y	300
Between groups	20–35 y (35)	36–50 y (40)	1,400
Between groups	20–35 y (35)	51–65 y (25)	875
Between groups	36–50 y (40)	51–65 y (25)	1,000
All strata			4,950

Notes: Impostor pairs are unordered ($n(n-1)/2$ within groups; $n_1 \times n_2$ between groups; total $100 \times 99 / 2$). Self-match scores did not differ among age groups (one-way ANOVA, $F = 0.962$, $p = 0.386$). Error rates by stratum are not shown (see text).

4. Discussion

4.1. Principal findings

In this pilot, a non-mydratic fundus image was obtained from all 100 volunteers without mydriasis and converted into a compact vessel descriptor in under two seconds per comparison. Discrimination recomputed from the tabulated scores was moderate (AUC about 0.89, d' 2.55, crossover near 18.5%), well below the near-perfect separation first reported. Because reference trials were self-matches, these values describe how different one person's image is from another's, not how reliably the same eye is recognized on re-imaging. No difference in mean self-match score was found among age groups, but the sample cannot establish age invariance.

4.2. Comparison with the literature

Retinal identification based on vessel landmarks and correlation has been reported since the mid-2000s,^{10,11} and retinal vessel biometrics has been reviewed alongside other vascular traits.^{12,13} The present pipeline, with matched-filter segmentation,^{20,21} skeletonization and fractal descriptors,²³ is conventional, and deep-learning segmentation is now widely studied.^{28–30} Error rates published for fingerprint, face and other modalities^{4,31} come from different protocols and populations and cannot be compared with a 100-person test with self-matched reference trials; no claim of superiority is made.

4.3. Interpretation and medicolegal implications

After death, loss of intraocular pressure, corneal clouding and segmentation of the retinal blood columns (the Kevorkian sign) are described, and their timing depends on eyelid position, temperature and humidity.^{14,16,17} No postmortem eye was imaged in this study, so no accuracy band or likelihood-ratio category can be stated and those of the submission were removed. The phases in Table 6 and Figure 5 are a hypothetical framework only. Antemortem retinal images will exist only for people who have had retinal imaging, which limits any gallery-based use in DVI.

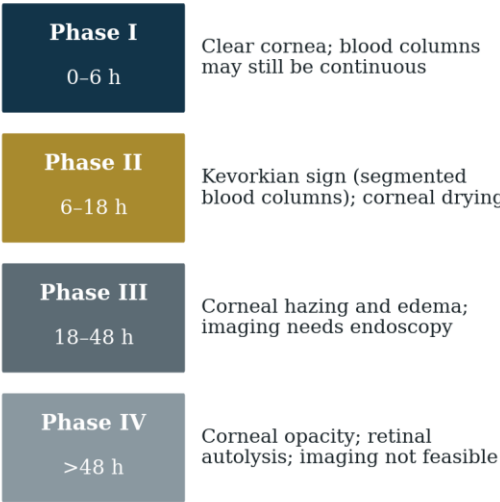
In Indonesian proceedings, medical findings usually reach the court through the *visum et repertum*,^{32,33} and expert testimony is among the means of evidence listed in the Criminal Procedure Code.³⁴ Whether a retinal comparison could support such testimony, and with what weight, is for the court and would require validated error rates from adequately designed studies. A likelihood-ratio statement needs calibrated score densities for same-source and different-source comparisons; the crude ratio of about 6 from Table 3 is not such an estimate, and 9,900 impostor comparisons could not resolve a ratio above about 10^4 . Biometric data are personal data, so storage, security and consent arrangements must be specified;^{27,35} this study did not test regulatory compliance.

Table 6. Hypothetical postmortem phases for retinal imaging (no postmortem data were collected).

Phase	Interval	Expected ocular findings	Imaging approach
I (immediate)	0–6 h	Clear cornea; blood columns may still be continuous	Non-mydriatic fundus camera, non-contact
II (early)	6–18 h	Kevorkian sign (segmented blood columns); corneal drying	Camera with topical wetting; hand-held funduscope
III (intermediate)	18–48 h	Corneal hazing and edema; retinal autolysis; main trunks distinguishable	Ophthalmic endoscopy at autopsy
IV (advanced)	> 48 h	Total corneal opacity; retinal liquefaction; ocular collapse	Conventional funduscopy not feasible

Notes: Intervals and findings are the author’s proposal. The accuracy bands (> 99% to < 50%) and likelihood-ratio categories of the submission were removed because no postmortem model or data were reported.

(a) Proposed postmortem phases (hypothetical)



(b) Proposed workflow

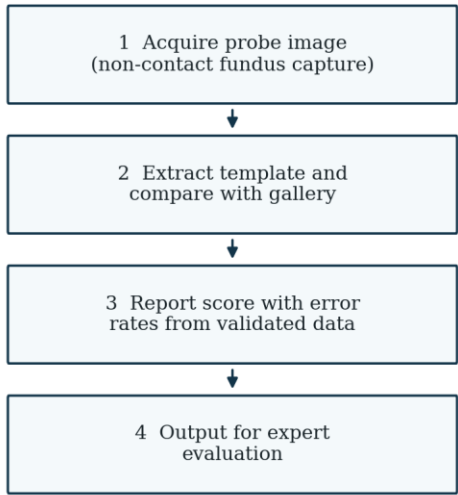


Figure 5. Hypothetical postmortem phases (a) and proposed workflow (b) for retinal comparison. No postmortem images were acquired; the framework is not derived from data.

4.4. Limitations

First, one image per person and self-matched reference trials mean that repeatability, image-quality variation and template aging were not tested. Second, the score definition, registration step and parameter tuning are incompletely specified, and w and θ may have been tuned on the same data. Third, the sample was 100 convenience volunteers from one city, imaged with one device, right eye only; the impostor total in Table 3 is inconsistent, raw scores were unavailable to this revision, and no comorbidity analysis was performed. Fourth, there were no cadaveric or antemortem–postmortem data. Fifth, legal and data-protection aspects were not studied. The pipeline should therefore be regarded as a feasibility prototype. A redesigned study should acquire at least two independent images per eye on separate occasions, separate development and test partitions, report error rates with participant-level confidence intervals and include cadaveric material.

5. Conclusion

In this pilot of 100 adults in Palembang, non-mydriatic retinal imaging and vessel matching were feasible and fast (1.50 s per comparison; about 1.76 s with pre-processing). Scores recomputed from the reported distributions showed moderate discrimination (AUC about 0.89). The design, with self-matched reference trials and no postmortem data, does not support claims of identification accuracy, age invariance or evidentiary admissibility, and

independent repeat captures, registration and cadaveric validation are required before use in disaster victim identification.

Declarations

Use of generative artificial intelligence. None. The author declares that no generative artificial intelligence tool was used in the conception, research, analysis, drafting, revision or preparation of this manuscript.

Author contributions. RA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. The author has read and approved the final version of the manuscript and agrees to be accountable for all aspects of the work.

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Conflict of interest. None. The author declares no competing financial or non-financial interests in relation to this work.

Ethical approval. The study was approved by CMHC Resesarch Center, Indonesia (approval no. 2024-092) and complied with the Declaration of Helsinki.

Consent for publication. Not applicable. Written informed consent was obtained from all participants for participation; no individually identifiable images or data are published.

Data availability. The de-identified feature values and comparison scores are available from the corresponding author on reasonable request.

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