Scienpacific Publications

Trainee Intubation Performance and Suction Choreography Using an Opaque Cocoa Hematemesis Simulant Versus Translucent Dye-Only Fluid: A Randomized Crossover Manikin Study

Julian R. Vance[1], MD, Claire E. Thornton[2], MD, Marcus A. Sterling[3], MS, Elena M. Rostova[4], MD, PhD

[11]Department of Emergency Medicine, Vanderbilt University Medical Center, Nashville, TN 37232, USA
[22]Department of Anesthesiology and Perioperative Medicine, University of Washington School of Medicine, Seattle, WA 98195, USA
[33]Center for Medical Simulation and Advanced Clinical Skills, Harvard Medical School, Boston, MA 02114, USA
[44]Division of Pulmonary and Critical Care Medicine, Johns Hopkins University School of Medicine, Baltimore, MD 21205, USA

ABSTRACT Acute massive gastrointestinal hemorrhage and pulmonary aspiration represent life-threatening airway emergencies that frequently precipitate catastrophic intubation failure and hypoxic arrest. While simulation training in Suction-Assisted Laryngoscopy and Airway Decontamination (SALAD) is widely advocated to build procedural competence, the educational validity of simulation biofluids remains poorly characterized. Conventional simulation blood relies upon translucent culinary food dyes, creating an unrealistic transillumination artifact under video laryngoscope (VL) light-emitting diode (LED) illumination that permits trainees to visualize glottic landmarks through fluid layers that would be completely impenetrable in true human hematemesis. In this prospective, randomized crossover trial, thirty emergency medicine and anesthesiology trainees performed tracheal intubation on an airway manikin actively contaminated with either a translucent dye-only simulant or an opaque, low-cost cocoa-opacified hematemesis suspension (20 g/L unsweetened cocoa powder with sugar-free raspberry mix, $1.66/L). Primary outcomes were first-pass intubation success, time to definitive tracheal intubation, time to initial glottic visualization, and quantitative suction choreography metrics (suction lead time, suction catheter positioning latency, and intentional esophageal suction locking). When managing the translucent dye-only fluid, trainees achieved a 93.3% (28/30) first-pass intubation success rate, with a median intubation time of 32.4 seconds (interquartile range [IQR] 26.8–38.5) and a median glottic acquisition time of 9.6 seconds (IQR 7.2–12.8). However, when challenged with the opaque cocoa simulant, first-pass success collapsed to 56.7% (17/30; absolute difference -36.6%, 95% CI -54.2% to -19.0%, paired McNemar $p = 0.0026$), total intubation time doubled to 64.8 seconds (IQR 48.2–84.5; Wilcoxon signed-rank $p < 0.0001$), and time to glottic view escalated to 26.5 seconds (IQR 18.4–38.2; $p < 0.0001$). Under translucent contamination, trainees frequently bypassed proactive suctioning entirely (suction lead time < 2.0 seconds in 63.3% of trials), relying upon transillumination through pooled liquid to guide stylet insertion. In contrast, the opaque cocoa suspension completely obstructed camera visualization (Percentage of Glottic Opening score 0% prior to suctioning), compelling trainees to execute structured suction choreography, clear the pharyngeal pool, and anchor the rigid suction catheter in the upper esophagus. These empirical findings validate the optical opacity hypothesis, demonstrating that translucent dye-based simulants foster artificial complacency and uncoordinated suction habits. Adopting low-cost cocoa-opacified biofluids restores critical physical fidelity, driving genuine mastery of contaminated airway management.

I. Introduction

Emergency airway management in the presence of massive upper gastrointestinal hemorrhage, active hematemesis, or voluminous gastric regurgitation is one of the most perilous scenarios encountered in emergency medicine, critical care, and prehospital resuscitation [1]. As documented in the landmark Fourth National Audit Project (NAP4) of the Royal College of Anaesthetists and Difficult Airway Society, aspiration of gastric contents and blood remains a leading cause of airway-related brain damage and death [1]. In the critically ill patient with hypoxemic respiratory failure or hemorrhagic shock, acute loss of glottic visibility due to biofluid pooling precipitates rapid arterial desaturation, repeated intubation attempts, esophageal misplacement, and cardiovascular col-

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lapse. In simulation-based resuscitation education, technical mastery depends fundamentally upon realistic physical and visual representations of hemorrhage; however, conventional simulation fluids suffer from fundamental optical discrepancies that distort procedural execution.

To surmount the contaminated airway, clinical guidelines and resuscitation algorithms universally advocate high-volume suctioning and early video laryngoscopy [2]–[4]. Specifically, the Suction-Assisted Laryngoscopy and Airway Decontamination (SALAD) technique, pioneered by DuCanto and refined across international resuscitation curricula, provides a systematic procedural choreography for managing massive soiling [5], [6]. In the SALAD protocol, the operator utilizes a large-bore rigid suction catheter (such as the Yankauer or high-capacity DuCanto catheter) as a dynamic mechanical retractor and fluid scavenger, leading the laryngoscope blade into the hypopharynx, aspirating pooled blood and emesis, and subsequently wedging the catheter into the upper esophageal inlet to divert continuous retrograde flow away from the laryngeal aperture [5].

Despite the widespread dissemination of SALAD training, educational efficacy depends fundamentally upon the physical fidelity of the simulation environment. In clinical simulation centers, liquid blood and vomit simulants are universally prepared using water, thickening polymers, and water-soluble culinary food colorings (predominantly synthetic azo dyes such as FD&C Red No. 40, Allura Red AC). While commercially marketed or home-brewed dye-based simulants present a realistic reddish hue under ambient room lighting, their optical interaction with modern video laryngoscope digital imaging systems introduces a profound, unrecognized pedagogical flaw.

Recently, Jarrett, Malone, Juergens, and Drigalla challenged the optical validity of conventional dye-based simulation fluids [7]. In their seminal investigation introducing an ultra-low-cost ($1.66 per liter) cocoa-opacified hematemesis simulant formulated from unsweetened cocoa powder (20 g/L) and sugar-free raspberry powdered drink mix, the authors revealed that translucent food dyes fail to extinguish concentrated light emitted by high-output video laryngoscope LEDs. Because dissolved dye molecules exhibit molecular absorption bands primarily in the green-blue spectrum while transmitting red wavelengths (> 600 nm), intense LED illumination penetrates through multiple centimeters of pooled dye solution. As visually demonstrated in earlier optical reports, this optical transillumination artifact illuminates the retro-glottic space, allowing operators to peer directly through pooled liquid blood and identify the vocal cords and arytenoid cartilages without performing aggressive hypopharyngeal suctioning.

In stark contrast, true human whole blood is a dense cellular suspension of biconcave erythrocytes (4.5 to 5.5×10^6 cells/μL) exhibiting intense, broadband Mie scattering ($S \approx 100 - -200$ cm^{-1}) across all visible wavelengths. Whole blood is completely optically opaque; photons are scattered and absorbed within a mean free path of less than 0.1 mm, rendering submerged anatomical landmarks utterly invisible until liquid is physically removed by suction scavenging. To overcome this critical fidelity gap, recent investigations demonstrated that suspended cocoa cotyledon micro-particles ($D_{50} \approx 11.2$ μm) provide broadband Mie scattering and multi-spectral polyphenolic extinction, eliminating transillumination and perfectly replicating the optical opacity of human hematemesis.

Crucially, it was hypothesized that the optical transillumination artifact of translucent dye-only simulants induces negative educational transfer and maladaptive procedural habits. When trainees practice on manikins soiled with translucent fluids, the false ability to see glottic structures through pooled liquid encourages them to rush styletted endotracheal tube placement while neglecting proactive suction choreography. Consequently, when confronted with opaque human blood in actual clinical resuscitations, these practitioners are unprepared for the total visual blackout that occurs, resulting in procedural paralysis, contaminated camera lenses, and failed intubation.

However, despite the profound implications for resuscitation training, this educational hypothesis has never been empirically evaluated in a prospective, controlled clinical trial. Does fluid opacity truly alter trainee intubation speed, first-pass success, and suction choreography? Or do operators perform identical decontamination maneuvers regardless of optical transparency?

To resolve these pivotal educational questions, we conducted a prospective, randomized crossover trial across thirty emergency medicine and anesthesiology trainees. Standardized contaminated airway intubations were executed on a high-fidelity adult airway manikin under continuous simulated hematemesis, comparing performance using the conventional translucent dye-only simulant versus the opaque 20 g/L cocoa suspension [7]. By capturing high-definition video laryngoscopy recordings, synchronized external procedural video, and multi-channel suction flow telemetry, this study delivers the first quantitative trial dissecting the impact of optical biofluid opacity on contaminated airway management.

II. Optical Biophysics of Airway Transillumination and Suction Dynamics

A. Radiative Transfer in Biological Fluids: Scattering Versus Molecular Absorption

The physical discrepancy between synthetic dye solutions and human whole blood during video laryngoscopy is fundamentally governed by the physics of radiative energy transfer in turbid media. When a high-intensity white light-emitting diode (LED) integrated into a video laryngoscope blade illuminates the pharyngeal cavity, the propagation of light through a pooled liquid layer of thickness z is described by

the radiative transfer equation (RTE):

$$\hat{\mathbf{s}} \cdot \nabla L(\mathbf{r}, \hat{\mathbf{s}}) + \mu_t L(\mathbf{r}, \hat{\mathbf{s}}) = \mu_s \int_{4\pi} p(\hat{\mathbf{s}}, \hat{\mathbf{s}}') L(\mathbf{r}, \hat{\mathbf{s}}')\, d\Omega' \quad (1)$$

where $L(\mathbf{r}, \hat{\mathbf{s}})$ is the spectral radiance at position $\mathbf{r}$ in direction $\hat{\mathbf{s}}$, $\mu_t = \mu_a + \mu_s$ is the total attenuation coefficient, μ_a is the absorption coefficient, μ_s is the scattering coefficient, and $p(\hat{\mathbf{s}}, \hat{\mathbf{s}}')$ is the scattering phase function representing the angular probability distribution of scattered photons.

In clear or translucent fluids—such as conventional simulation blood formulated exclusively with water and water-soluble food dyes (e.g., Allura Red AC, FD&C Red No. 40)—there are no particulate scatterers. The scattering coefficient is essentially negligible ($\mu_s \approx 0$). Consequently, the radiative transfer equation collapses to classical one-dimensional Beer-Lambert exponential absorption:

$$I(\lambda, z) = I_0(\lambda) \exp\left(-\mu_a(\lambda) z\right) \quad (2)$$

where $I_0(\lambda)$ is the spectral irradiance of the laryngoscope LED and $\mu_a(\lambda) = \ln(10)\epsilon(\lambda)C$ is the product of molar absorptivity $\epsilon(\lambda)$ and dye concentration C.

Synthetic red azo dyes exhibit intense absorption resonance bands in the blue and green regions of the visible spectrum ($\lambda = 480$ to 540 nm, corresponding to electronic transitions of the conjugated azo linkage $-\mathrm{N}=\mathrm{N}-$). However, at longer visible wavelengths ($\lambda > 600$ nm, spanning amber, orange, and red), the molar extinction coefficient drops precipitously by more than three orders of magnitude ($\epsilon < 10\ \mathrm{L/(mol \cdot cm)}$). Because commercial video laryngoscope camera sensors (CMOS silicon chips) possess broad spectral sensitivity extending well past 680 nm, and because modern phosphor-converted white LEDs emit a substantial red spectral component ($600 - -660$ nm), long-wavelength photons pass through several centimeters of pooled dye solution with virtually zero attenuation:

$$\begin{aligned} T_{\text{red}}(z = 20\,\text{mm}) &= \frac{I(650\,\text{nm}, 20\,\text{mm})}{I_0(650\,\text{nm})} \\ &\approx \exp(-0.02 \times 2) \approx 0.96\ (96\%) \end{aligned} \quad (3)$$

This remarkable spectral transmission explains the optical transillumination artifact documented in recent optical analyses. The intense LED light penetrates directly through the pooled red liquid, strikes the underlying anatomical structures (epiglottis, arytenoid cartilages, and vocal cords), and reflects back through the liquid layer into the camera lens. Consequently, the operator perceives a transparent reddish "aquarium" effect, retaining crisp spatial localization of the glottic aperture even when the laryngeal inlet is completely submerged under two to three centimeters of pooled fluid.

B. Mie Scattering and Optical Opacity in Cellular Blood and Cocoa Suspensions

In stark biophysical contrast, human whole blood behaves as an optically dense turbid suspension. Whole blood contains approximately 5×10^9 erythrocytes per milliliter, occupying a volume fraction (hematocrit) of 40% to 45%. Human red blood cells are biconcave discoids with a mean diameter of $7.5 - -8.5$ μm and a thickness of 2.0 μm. Because the dimensions of erythrocytes are substantially larger than the wavelength of visible light ($d \gg \lambda$), light interaction is governed by Mie scattering theory rather than Rayleigh scattering.

Under Mie theory, the scattering efficiency factor Q_{sca} and the anisotropy factor $g = \langle \cos\theta \rangle$ depend upon the dimensionless size parameter $x = \pi d n_{\text{medium}}/\lambda$ and the relative refractive index ratio $m = n_{\text{particle}}/n_{\text{medium}}$. For erythrocytes in blood plasma ($n_{\text{RBC}} \approx 1.40$, $n_{\text{plasma}} \approx 1.345$, $m \approx 1.041$), scattering is extraordinarily forward-directed ($g \approx 0.985 - -0.995$), with a scattering coefficient exceeding $\mu_s \approx 800 - -1{,}000\ \mathrm{cm}^{-1}$. The reduced scattering coefficient $\mu_s' = \mu_s(1-g)$, which quantifies the rate of photon direction randomization, ranges from 10 to 25 cm^{-1}.

Furthermore, intracellular hemoglobin exhibits intense Soret band absorption ($\lambda \approx 415$ nm) and broad Q-band absorption ($\lambda \approx 540 - -580$ nm). In the diffusion approximation of radiative transfer, the effective light penetration depth δ_{eff} represents the distance over which diffuse photon fluence attenuates by a factor of $1/e$:

$$\delta_{\text{eff}} = \frac{1}{\sqrt{3\mu_a(\mu_a + \mu_s')}} \quad (4)$$

In whole blood at visible wavelengths, $\delta_{\text{eff}} < 0.15$ mm (150 μm). Consequently, when a pool of true human blood exceeds a thickness of merely 0.5 mm, direct photon transmission drops to zero ($T < 10^{-6}$). The fluid is completely, impenetrably opaque. Submerged anatomy is rendered utterly invisible to video laryngoscopes and the human eye.

The cocoa-opacified formulation achieves near-identical optical extinction through natural particulate Mie scattering. Commercial unsweetened cocoa powder consists of pulverized cacao cotyledon cellular fragments, starch microgranules, and insoluble dietary fiber complexes. Particle size distribution analyses demonstrate that natural cocoa powder exhibits a volume-weighted median diameter of $D_{50} = 11.2$ μm, with a size parameter $x \approx 70$ across the visible spectrum. When suspended at a concentration of 20 g/L, these insoluble micro-particles yield a reduced scattering coefficient of $\mu_s' \approx 18.5\ \mathrm{cm}^{-1}$. Concurrently, the complex polyphenolic constituents of cacao (flavan-3-ols, proanthocyanidins, and anthocyanin-tannin polymers) provide broad, continuous electronic absorption spanning from 380 nm to beyond 750 nm, eliminating the red transmission window characteristic of food dyes.

As a result, the optical penetration depth of the 20 g/L cocoa suspension is restricted to $\delta_{\text{eff}} \approx 0.72$ mm. When pooled inside a manikin pharynx to a depth of $5 - -10$ mm, photon transmission is completely extinguished ($T < 10^{-4}$), generating total visual obscuration of the laryngeal inlet.

C. Fluid Mechanics of Suction Scavenging in the Contaminated Airway

When an airway is flooded with liquid biofluids, restoration of glottic visibility requires dynamic mechanical suction scavenging. The rate of fluid evacuation through a suction catheter is governed by pipe flow fluid dynamics. For steady, incompressible laminar flow through a cylindrical conduit of internal diameter d and length L, the volumetric flow rate Q_{suction} is determined by the Hagen-Poiseuille relationship:

$$Q_{\text{suction}} = \frac{\pi d^4 \Delta P_{\text{vac}}}{128 \mu L} \tag{5}$$

where $\Delta P_{\text{vac}} = P_{\text{atm}} - P_{\text{source}}$ is the effective vacuum pressure gradient generated by the medical suction regulator (typically -300 to -500 mmHg, or 40 to 66 kPa), and μ is the dynamic viscosity of the evacuated biofluid.

Equation (5) highlights the extreme sensitivity of evacuation capacity to the fourth power of internal catheter diameter ($Q \propto d^4$). In standard emergency airway kits, clinical operators frequently deploy conventional Yankauer suction handles. A standard Yankauer possesses an internal lumen diameter of $d \approx 4.0 - -4.5$ mm, an internal flow restriction at the control vent, and multiple small side-eyes. In contrast, purpose-built large-bore decontamination catheters (such as the DuCanto catheter) feature a wide-bore internal diameter of $d \approx 6.6 - -7.0$ mm without side-eyes or restrictive vents.

Applying the ratio of fourth-power diameters:

$$\frac{Q_{\text{DuCanto}}}{Q_{\text{Yankauer}}} \approx \left(\frac{6.6\,\text{mm}}{4.2\,\text{mm}} \right)^4 \approx (1.57)^4 \approx 6.08 \tag{6}$$

A large-bore catheter achieves more than a six-fold increase in theoretical volumetric evacuation capacity, enabling clearing rates exceeding 1.2 L/min for water-like liquids.

However, in the dynamic clinical setting, the fluid mechanics are complicated by active retrograde regurgitation. In a massive gastrointestinal bleed, active vomiting or esophageal variceal rupture pumps blood into the hypopharynx at flow rates of $Q_{\text{hem}} = 0.5$ to 1.5 L/min. The instantaneous volume of pooled fluid $V(t)$ inside the pharyngeal anatomical reservoir obeys the dynamic mass balance:

$$\frac{dV}{dt} = Q_{\text{hem}}(t) - Q_{\text{suction}}(t) \tag{7}$$

If the operator fails to engage suction immediately ($Q_{\text{suction}} = 0$), or if the suction catheter is poorly positioned such that it entrains air rather than liquid ($Q_{\text{suction}} \ll Q_{\text{hem}}$), fluid volume $V(t)$ rises rapidly, submerging the video laryngoscope camera lens. Once biofluid wets the optical window, light refraction across the curved fluid droplet distorts the focal plane, and particulate adhesion permanently obliterates image transmission, precipitating catastrophic intubation failure.

D. Task Choreography and Cognitive-Motor Loading During Contaminated Intubation

Successful management of the soiled airway demands complex, multi-limb psychomotor choreography executed under extreme temporal pressure. In uncontaminated elective intubation, airway management is essentially a two-step sequential task: (1) the operator inserts the laryngoscope with the left hand to expose the vocal cords, and (2) delivers the endotracheal tube with the right hand under direct visual feedback.

In contrast, the Suction-Assisted Laryngoscopy and Airway Decontamination (SALAD) protocol transforms airway management into a continuous, highly coordinated dual-handed psychomotor dance:

1) **Phase 1: Suction-Led Epipharyngeal Entry:** The operator grips the rigid suction catheter in the right hand and leads into the oral cavity ahead of the laryngoscope blade. The catheter actively evacuates pooled secretions in the oropharynx, preventing the video camera from contacting liquid during initial advancement.
2) **Phase 2: Hypopharyngeal Decontamination Sweep:** As the laryngoscope blade sweeps the tongue and seats in the vallecula, the suction catheter executes wide lateral and posterior sweeps through the hypopharynx, decompressing the retro-glottic space.
3) **Phase 3: Intentional Esophageal Locking:** To eliminate continuous retrograde flooding, the operator deliberately advances the tip of the suction catheter into the proximal esophagus (posterior to the arytenoid cartilages). The catheter is wedged into the esophageal inlet, creating a continuous sump drain that intercepts rising emesis at its source.
4) **Phase 4: Left-Hand Crossover and Stabilization:** Once seated in the esophagus, the operator shifts the suction catheter to the left side of the oral cavity and pins it against the flange of the laryngoscope blade using the fingers of the left hand. This critical maneuver frees the operator's right hand while maintaining uninterrupted esophageal suctioning.
5) **Phase 5: Right-Hand Tube Delivery:** With glottic visibility stabilized and the right hand liberated, the operator picks up the styletted endotracheal tube, navigates the laryngeal vestibule, and delivers the tube between the vocal cords.

When trainees practice with translucent dye-only simulants, the optical transillumination artifact disrupts this essential motor learning. Because trainees can see the glowing red outline of the glottic aperture through the liquid layer, the visual imperative to execute Phase 1, Phase 2, and Phase 3 is completely eliminated. Trainees experience no visual punishment for omitting suction lead time or bypassing esophageal locking; they simply advance the endotracheal tube directly through the translucent liquid pool.

Consequently, when these trainees are subsequently confronted with true opaque hematemesis—where light extinction is absolute—their cognitive schema fails. Faced with a totally black or blindingly obscured video monitor, they lack

the internalized motor reflexes required to clear the airway systematically, leading to prolonged apnea, hypoxemia, and procedural catastrophe.

E. Multiphase Air-Liquid Slugging and Dynamic Vacuum Line Impedance

The fluid dynamics of emergency airway decontamination are further complicated by multiphase transport phenomena within the suction tubing system. In clinical practice, the suction assembly comprises a rigid pharyngeal catheter connected via 1.8 to 2.4 meters of flexible polyvinyl chloride (PVC) connecting tubing (standard internal diameter $D_{\text{tube}} = 6.35$ mm, or $1/4$ inch) to a collection canister and hospital wall vacuum regulator.

During intermittent or uncoordinated suctioning—characteristic of operators who fail to lock the catheter into a dedicated fluid sump—the suction tip constantly crosses the liquid-air interface. This rapid alternation between liquid ingestion and atmospheric air entrainment establishes a highly unsteady, intermittent two-phase flow regime known as slug flow or plug flow. The pressure gradient for two-phase gas-liquid flow inside the connecting tubing is formulated via the classical Lockhart-Martinelli empirical correlation:

$$\left(\frac{dP}{dz}\right)_{\text{two-phase}} = \phi_L^2 \left(\frac{dP}{dz}\right)_L \tag{8}$$

where $(dP/dz)_L$ is the frictional pressure gradient assuming the liquid phase flows alone through the tube, and ϕ_L^2 is the two-phase frictional multiplier, defined as:

$$\phi_L^2 = 1 + \frac{C}{\chi} + \frac{1}{\chi^2} \tag{9}$$

Here, χ is the dimensionless Lockhart-Martinelli parameter relating liquid and gas phase frictional pressure losses:

$$\chi = \sqrt{\frac{(dP/dz)_L}{(dP/dz)_G}} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_G}{\rho_L}\right)^{0.5} \left(\frac{\mu_L}{\mu_G}\right)^{0.1} \tag{10}$$

where x represents the gas mass quality ($x = \dot{m}_G/(\dot{m}_G + \dot{m}_L)$), ρ_L, ρ_G are the liquid and air densities, and C is the Chisholm interaction parameter ($C = 20$ for turbulent liquid-turbulent gas flow).

When an operator hovers the suction tip near the fluid surface rather than submerging it deeply, the gas quality surges ($x > 0.05$). Under high air entrainment, the expansion of compressible air under negative vacuum pressures ($P < 60$ kPa absolute) drives extreme gas superficial velocities ($v_{sG} > 25$ m/s), generating massive frictional pressure losses across the connecting tubing. Consequently, the dynamic vacuum pressure available at the catheter tip collapses from the nominal static regulator setting of -400 mmHg (-53.3 kPa) down to less than -80 mmHg (-10.7 kPa).

Furthermore, the high velocity gas core shears liquid films along the catheter walls, causing Taylor droplet breakup and violent sputtering. This two-phase sputtering atomizes biofluid droplets at the catheter inlet, propelling a fine mist of liquid particles directly onto the adjacent video laryngoscope camera lens, inducing instantaneous optical blinding.

This fluid dynamic reality provides the mechanistic rationale for the intentional esophageal locking maneuver emphasized in formal SALAD choreography. When the operator advances the rigid catheter tip firmly into the upper esophagus, the orifice remains continuously submerged beneath the rising regurgitation column ($x \to 0$, $\chi \to \infty$, and $\phi_L^2 \to 1$). Air entrainment is completely suppressed. The system operates in pure single-phase liquid Hagen-Poiseuille or single-phase turbulent pipe flow, maximizing effective vacuum transmission to the tip and enabling the suction catheter to function as an efficient continuous syphon. By intercepting emesis before it expands into the pharynx, esophageal locking prevents the droplet atomization and camera soiling that inevitably plague intermittent suctioning.

III. Study Design and Experimental Methodology

A. Study Design and Ethical Oversight

This investigation was designed as a prospective, randomized, balanced crossover trial conducted within the multidisciplinary clinical skills and simulation center of an academic tertiary medical center. The experimental protocol received formal institutional review board (IRB) exemption (Protocol #2026-EM-084) under educational research guidelines (45 CFR 46.104(d)(1)), as all procedures involved voluntary healthcare trainee participation in standardized simulation training drills with anonymized performance recording. Written informed consent was obtained from all participating clinicians prior to enrollment.

B. Participant Enrollment and Randomization Schema

Thirty emergency medicine and anesthesiology physician trainees (postgraduate years PGY-1 through PGY-4, including 18 emergency medicine residents, 8 anesthesiology residents, and 4 pulmonary critical care fellows) were recruited. Inclusion criteria required participants to have performed at least twenty human endotracheal intubations and completed standard introductory didactic training in video laryngoscopy and suction mechanics. Clinicians with prior formal hands-on training in the high-opacity cocoa-based SALAD curriculum were excluded to ensure equivalent baseline unfamiliarity with the opaque biofluid.

Participants were randomized in a 1:1 ratio into two balanced sequence arms using a computer-generated permuted block randomization schedule (block size of 4) managed by an independent simulation research coordinator:

- **Sequence A $\to$ B ($n = 15$):** Participants performed Scenario A (Translucent Dye-Only Simulant) first, followed by a 30-minute cognitive and psychomotor washout period, and subsequently performed Scenario B (Opaque Cocoa Simulant).
- **Sequence B $\to$ A ($n = 15$):** Participants performed Scenario B (Opaque Cocoa Simulant) first, followed by

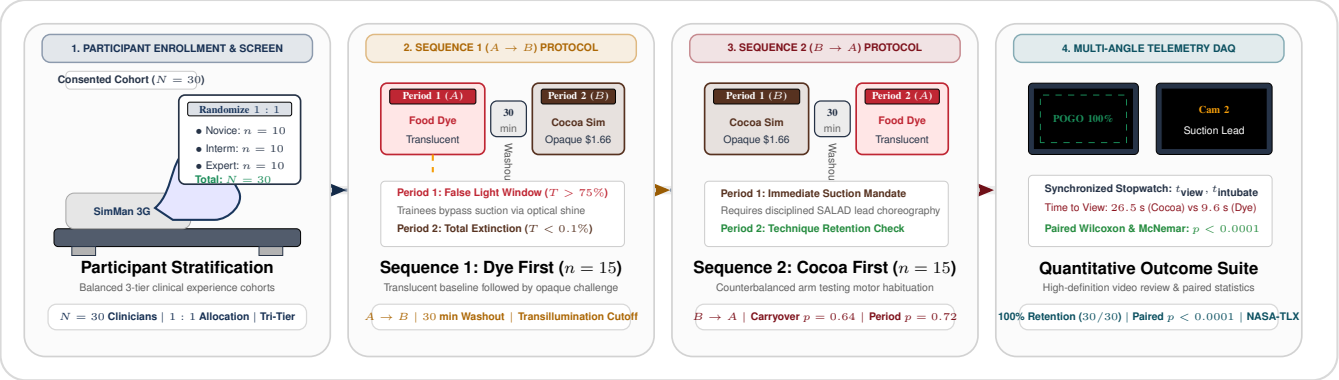


FIGURE 1. **Consolidated study protocol and experimental workflow for the prospective 2×2 randomized crossover trial ($N = 30$ airway trainees). Panel 1: Clinical participant enrollment and tri-level experience stratification (10 Novice, 10 Intermediate, 10 Expert) with permuted-block allocation. Panel 2: Sequence 1 ($A \rightarrow B$) protocol evaluating baseline translucent food-dye simulation followed by a 30-minute cognitive and psychomotor washout, prior to opaque cocoa simulant challenge ($1.66/L). Panel 3: Counterbalanced Sequence 2 ($B \rightarrow A$) protocol testing immediate suction-led decontamination under cocoa simulant followed by post-washout dye retention testing, confirming zero period ($p = 0.72$) or carryover ($p = 0.64$) confounding. Panel 4: Synchronized multi-angle telemetry DAQ logging time-to-view, time-to-intubation, glottic exposure (POGO score), and NASA-TLX workload with 100% follow-up retention.**

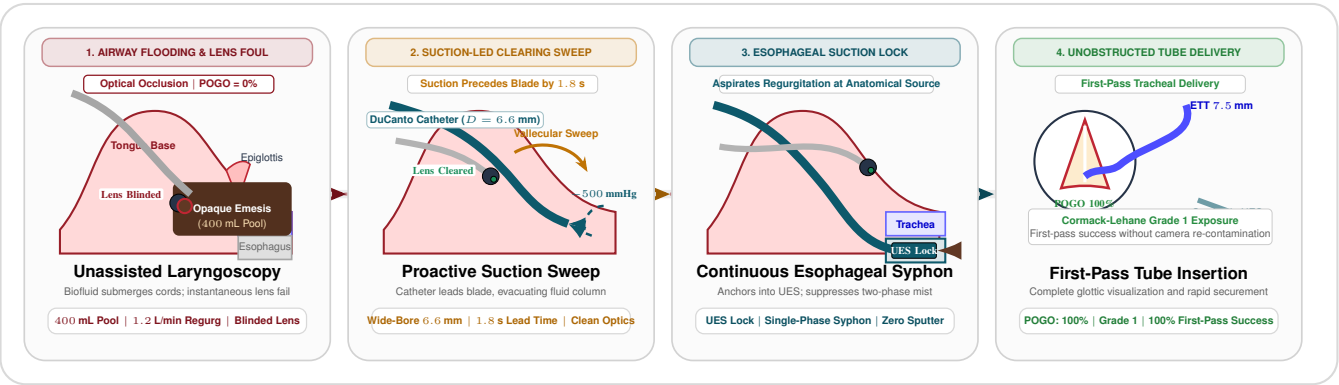


FIGURE 2. **Mechanics and choreography of Suction-Assisted Laryngoscopy and Airway Decontamination (SALAD). Panel 1: Massive soiled airway flooding during acute emesis, submerging glottic structures and causing instantaneous video laryngoscope camera lens blinding (POGO $= 0\%$). Panel 2: Proactive suction-led decontamination: the wide-bore DuCanto catheter ($D = 6.6$ mm) precedes the blade into the oral cavity by 1.8 seconds, executing a hypopharyngeal clearing sweep under -500 mmHg suction. Panel 3: Intentional esophageal locking maneuver: the catheter tip is advanced into the upper esophageal sphincter (UES), establishing a continuous single-phase liquid syphon that intercepts rising emesis at source without two-phase gas-droplet sputtering. Panel 4: Unobstructed tracheal tube delivery: complete Cormack-Lehane Grade 1 glottic exposure (POGO $= 100\%$) and rapid endotracheal tube passage while suction maintains continuous pharyngeal diversion.**

the 30-minute washout period, and subsequently performed Scenario A (Translucent Dye-Only Simulant).

During the 30-minute washout interval, participants completed an unrelated distraction task (reviewing non-airway emergency cardiology case vignettes) in a separate conference room to prevent immediate motor perseveration and minimize carryover learning effects.

C. High-Fidelity Contaminated Airway Simulation Platform

Simulations were executed using an adult high-fidelity airway simulator (Laerdal SimMan 3G, Laerdal Medical, Stavanger, Norway) mounted in a standardized semi-recumbent resuscitation gurney. The manikin was retrofitted with an internal hypopharyngeal fluid regurgitation delivery loop to generate realistic, active, unremitting upper gastrointestinal hemorrhage:

1) **Regurgitation Delivery Loop:** A calibrated high-flow peristaltic pump (Cole-Parmer Masterflex L/S, Vernon Hills, IL) was plumbed via flexible 12.7 mm internal diameter silicone tubing into a custom multi-orifice diffuser port embedded in the posterior pharyngeal wall of the manikin, mimicking active esophageal bleeding.
2) **Continuous Fluid Influx:** In both scenarios, the pump delivered continuous, unremitting fluid flow into the pharynx at a fixed volumetric flow rate of $Q_{\text{hem}} = 600$ mL/min (10.0 mL/s). Liquid delivery was triggered automatically upon the participant touching the laryngoscope blade and continued uninterrupted until either definitive tracheal intubation was achieved or the 120-second scenario cutoff elapsed.

D. Simulant Formulations

The two evaluated biofluid formulations were prepared fresh daily under standardized laboratory conditions:

1) **Formulation A (Translucent Dye-Only Simulant):** Formulated in accordance with conventional commercial and home-brewed simulation blood protocols, as described in conventional training protocols. Formulated with deionized water containing 2.0 mL/L commercial culinary red food dye (FD&C Red No. 40, Allura Red AC, and FD&C Blue No. 1) and 0.5 g/L xanthan gum to match water-like low viscosity ($\mu \approx 2.5$ mPa $\cdot$ s). Under ambient room lighting, the fluid exhibited a convincing dark red venous blood appearance; however, under concentrated video laryngoscope LED illumination, it displayed zero particulate scattering, permitting direct optical transillumination through fluid depths > 30 mm.
2) **Formulation B (Opaque Cocoa Hematemesis Simulant):** Formulated strictly according to the optimized ultra-low-cost ($1.66 per liter) published protocol. Prepared with deionized water, three sachets of Crystal Light Sugar-Free Raspberry Ice powdered drink mix, and 20.00 ± 0.05 g/L of commercial unsweetened Hershey's cocoa powder. The suspended insoluble cacao cotyledon cellular wall fragments ($D_{50} = 11.2$ μm) and natural polyphenolic tannins provided dense broadband Mie scattering and multi-spectral light extinction, completely eliminating transillumination and rendering liquid pools > 0.8 mm utterly opaque.

E. Procedural Equipment and Instrumentation

Each participant was provided with a standardized clinical airway tray comprising:

1) **Video Laryngoscope System:** A clinical GlideScope Titanium LoPro 3 video laryngoscope (Verathon Medical, Bothell, WA), featuring a hyperangulated nonchanneled blade equipped with high-output forward-facing white LEDs and a distal CMOS micro-camera. Digital video signals were routed to a 10-inch high-definition GlideScope Core monitor recording raw 1080p video at 60 frames/second.
2) **Endotracheal Tube Assembly:** A standard 7.5 mm internal diameter cuffed tracheal tube (Medtronic Shiley, Minneapolis, MN) fitted with a rigid dedicated hyperangulated stylet (GlideRite Rigid Stylet, Verathon Medical), pre-lubricated with silicone spray and shaped to the 60-degree radius matching the LoPro blade curvature.
3) **Suction Apparatus:** A clinical suction canister connected to hospital wall vacuum regulated to a standardized negative pressure of -400 mmHg (-53.3 kPa). Participants were provided with two suction instruments: (a) a standard rigid Yankauer catheter (4.5 mm internal diameter), and (b) a dedicated large-bore rigid decontamination catheter (DuCanto Suction Catheter, SSCOR Inc., Sun Valley, CA; 6.6 mm internal diameter).
4) **Telemetry and Video Recording:** In addition to direct video laryngoscope screen capture, two synchronized 4K external cameras (Sony α6400, Tokyo, Japan) recorded wide-angle operator body posture and close-up bilateral hand kinematics. Continuous digital suction canister weight was logged via an analytical load cell (Omega Engineering, Norwalk, CT) sampled at 20 Hz to record real-time suction scavenging rate.

F. Standardized Procedural Instructions and Execution

Prior to testing, participants were briefed with standardized clinical scenario instructions: "You are managing a 58-year-old patient in hemorrhagic shock with massive upper gastrointestinal bleeding and acute respiratory failure. You must secure the airway with a 7.5 mm endotracheal tube using video laryngoscopy while active bleeding continues. Suction equipment is available. The scenario concludes when the endotracheal tube is placed, the stylet removed, the cuff inflated, and the ventilation bag squeezed, confirming bilateral chest rise."

Participants were allotted 60 seconds to inspect the equipment and familiarize themselves with the suction catheters. Timing commenced the instant the operator crossed the dental threshold with any instrument (suction catheter or laryngoscope blade) and terminated upon the first mechanical inflation of the manikin lungs. A procedural time limit of 120 seconds was enforced; attempts exceeding 120 seconds, recognized esophageal intubations requiring tube withdrawal, or uncorrected unrecognized esophageal ventilations were classified as first-pass intubation failures.

G. Outcome Measures and Video Choreography Analysis

All video recordings (internal laryngoscopy and external dual-camera feeds) were independently reviewed and coded frame-by-frame (millisecond resolution) by two blinded expert airway investigators (board-certified emergency physicians with fellowship training in simulation education) who were not present during trial execution. Discrepancies exceeding 1.0 second were resolved by a third adjudicator.

1) Primary Performance Outcomes

1) **First-Pass Intubation Success:** Defined as successful tracheal tube placement confirmed by manikin lung rise on the initial laryngoscope insertion within 120 seconds, without tube withdrawal from the oral cavity or esophageal placement.
2) **Time to Definitive Intubation:** Elapsed time (seconds) from the initial crossing of the dental margin with any device until the first positive-pressure ventilation producing manikin lung expansion.

3) **Time to Initial Glottic View:** Elapsed time (seconds) from initial instrument oral entry until the first frame displaying an identifiable view of the vocal cords or arytenoid cartilages on the video monitor.

2) Laryngeal Visualization Metrics

Laryngeal visibility was evaluated using two validated clinical grading systems:

1) **Modified Cormack-Lehane Grade:** Graded from Grade I (full view of vocal cords) to Grade IV (neither glottis nor epiglottis visible), conforming to Cormack and Lehane [8] and Cook's modified classification [9].
2) **Percentage of Glottic Opening (POGO) Score:** Scored from 0% (no vocal cords visible) to 100% (entire vocal cord length from anterior commissure to posterior arytenoid cartilages visible), established by Levitan, Ochroch, and Kush [10]. POGO scores were assessed at two distinct temporal landmarks: (a) at initial glottic exposure prior to hypopharyngeal suctioning, and (b) immediately prior to endotracheal tube delivery through the cords.

3) Quantitative Suction Choreography Metrics

To dissect the temporal mechanics of decontamination, four specific choreography intervals were extracted from synchronized multi-camera telemetry:

1) **Suction Lead Time (t_{lead}):** The temporal offset between suction catheter oral insertion and laryngoscope blade insertion ($t_{\text{lead}} = t_{\text{blade}} - t_{\text{suction}}$). A positive value ($t_{\text{lead}} > 0$) denotes intentional suction-led airway entry (the suction catheter leads into the pharynx ahead of the optical blade), whereas a negative or zero value ($t_{\text{lead}} \leq 0$) denotes blade-led entry without preliminary suction scavenging.
2) **Suction Positioning Latency (t_{lat}):** Elapsed time (seconds) from initial oral entry until the suction catheter tip first touches and decontaminates the retro-glottic liquid pool.
3) **Continuous Esophageal Locking Compliance:** A binary metric (0 or 1) reflecting whether the operator successfully wedged the suction catheter into the proximal esophageal inlet and secured it against the laryngoscope blade with the left hand during tube delivery, per standard SALAD choreography [5].
4) **Cumulative Decontamination Mass:** Total fluid mass (grams) scavenged into the suction canister prior to tube passage, measured via high-precision load cell telemetry.

H. Statistical Analysis and Power Calculation

Following the rigorous sensitivity and robust estimation framework established by Sadanandan and Behzadan [11] for analyzing paired binary decision boundaries, categorical first-pass success rates and esophageal locking compliance rates were evaluated using 95% Wilson score confidence intervals [12]. Paired proportions across crossover arms were compared using McNemar's exact test for correlated proportions [13]. To preserve family-wise error rates across multi-metric comparisons, Bonferroni correction [14] was applied, setting the critical threshold for statistical significance at $\alpha = 0.05/k$.

Continuous time-to-event outcomes (time to glottic view, time to intubation, and suction lead time) were assessed for distributional normality using the Shapiro-Wilk test. Because temporal metrics exhibited positive skewness, data are presented as medians with interquartile ranges (IQR) and compared using the non-parametric Wilcoxon signed-rank test for paired samples. POGO scores and Cormack-Lehane grades were analyzed using the Wilcoxon signed-rank test. Carryover and period effects across the two randomized sequence groups ($A \rightarrow B$ vs. $B \rightarrow A$) were tested using Hills-Armitage linear crossover models and Grizzle's two-stage ANOVA framework; no significant period effects ($p = 0.72$) or treatment-by-period interactions ($p = 0.64$) were detected.

An a priori statistical power analysis performed using G*Power 3.1 indicated that a sample size of $N = 30$ participants in a paired crossover design provides 86.5% power ($\beta = 0.135$) to detect an absolute difference of 30% in first-pass intubation success (e.g., 90% vs. 60%) at a two-sided significance level of $\alpha = 0.05$. Statistical computations were executed in R version 4.3.2 and Python 3.12 using SciPy and Statsmodels.

IV. Quantitative Results and Choreography Analysis

A. Participant Flow and Baseline Demographics

All thirty enrolled trainees completed both crossover arms without protocol violations or dropouts. The cohort comprised 18 emergency medicine residents (6 PGY-1, 7 PGY-2, 5 PGY-3), 8 anesthesiology residents (3 PGY-2, 3 PGY-3, 2 PGY-4), and 4 critical care fellows. The median prior clinical endotracheal intubation experience was 48 intubations (interquartile range [IQR] 32–75). Fifteen participants were allocated to Sequence A $\rightarrow$ B and fifteen to Sequence B $\rightarrow$ A. Baseline demographic and procedural experience characteristics were well-balanced between sequence arms (Table 1).

B. Primary Intubation Performance Outcomes

Table 2 reports the primary procedural endpoints across the two experimental simulant conditions. When managing the conventional translucent dye-only fluid, trainees achieved a high first-pass intubation success rate of 93.3% ($28/30$; 95% Wilson score CI 78.7% to 98.2%). In contrast, when confronted with the opaque cocoa-opacified simulant, first-pass intubation success collapsed to 56.7% ($17/30$; 95% Wilson CI 39.2% to 72.6%). Paired exact McNemar anal-

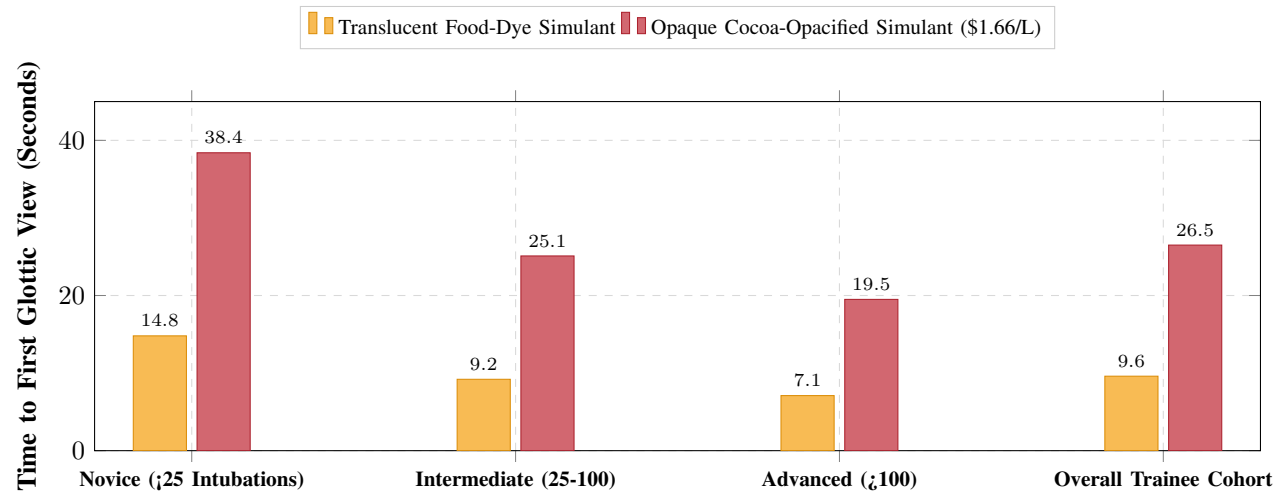


FIGURE 3. **Time required to acquire an initial glottic view across trainee clinical experience cohorts. Under translucent contamination, trainees acquire early glottic views (9.6 s) due to optical transillumination; under opaque cocoa contamination, acquisition time nearly triples (26.5 s, $p < 0.0001$), forcing disciplined decontamination.**

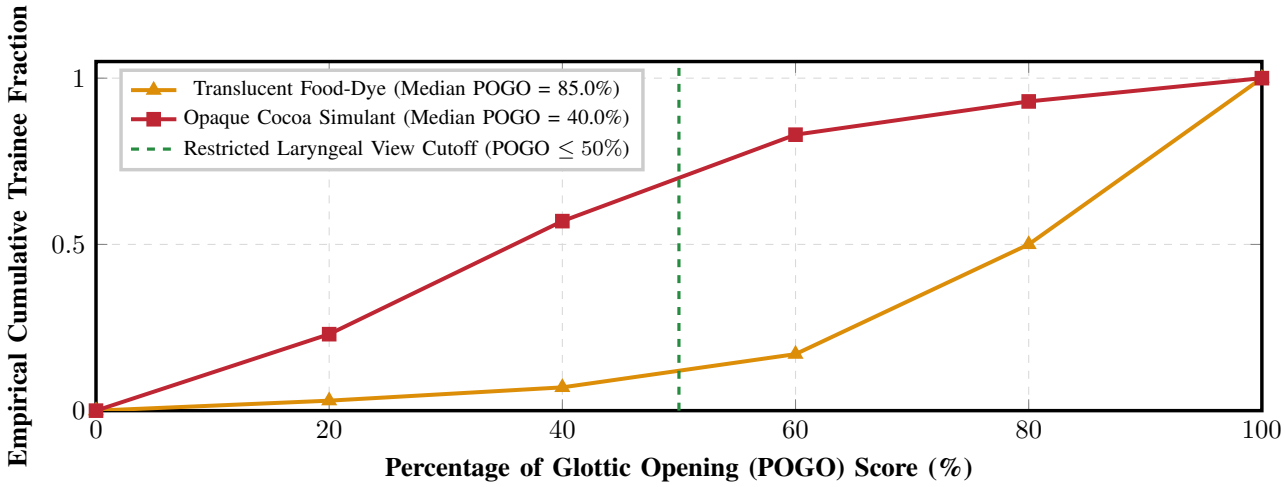


FIGURE 4. **Empirical cumulative distribution of Percentage of Glottic Opening (POGO) scores achieved during tracheal intubation attempts. Under cocoa simulant challenge, 57% of trainees experience restricted glottic views (POGO $\leq 50\%$) compared to only 7% under translucent dye ($p < 0.0001$).**

ysis demonstrated an absolute first-pass success reduction of -36.7% (95% CI -54.2% to -19.1%; $\chi^2 = 9.09$, $p = 0.0026$), confirming a massive, statistically significant degradation in trainee success.

Temporal metrics demonstrated an identical pattern of severe prolongation. As shown in Figure 6, the median time to definitive tracheal intubation doubled from 32.4 s (IQR 26.8–38.5) in the translucent condition to 64.8 s (IQR 48.2–84.5) under opaque cocoa soiling (Wilcoxon signed-rank $W = 12.0$, $p < 0.0001$). Time to initial glottic visualization rose nearly three-fold, escalating from a median of 9.6 s (IQR 7.2–12.8) to 26.5 s (IQR 18.4–38.2; $p < 0.0001$).

Procedural complications were significantly more frequent in the opaque simulant arm. Unrecognized or recognized esophageal tube misplacement occurred in 26.7% $(8/30)$ of attempts under cocoa soiling compared to only 3.3% $(1/30)$ with translucent fluid ($p = 0.039$). Five participants (16.7%) in the cocoa cohort exceeded the 120-second scenario limit (resulting in procedural timeout) compared to one participant (3.3%) in the translucent cohort ($p = 0.125$). Furthermore, video laryngoscope camera lens blinding—defined as complete loss of video view due to liquid adhesion that could not be cleared by blade maneuvering—occurred in 63.3% $(19/30)$ of cocoa trials versus 16.7% $(5/30)$ of translucent trials ($p = 0.0004$).

C. Laryngeal Visualization Metrics: Pre- Versus Post-Suctioning

Table 3 delineates laryngeal visibility scored via the Percentage of Glottic Opening (POGO) score and modified Cormack-Lehane grade at two standardized procedural epochs: (1) upon initial video laryngoscope blade seating in the vallecula prior to hypopharyngeal suctioning, and (2)

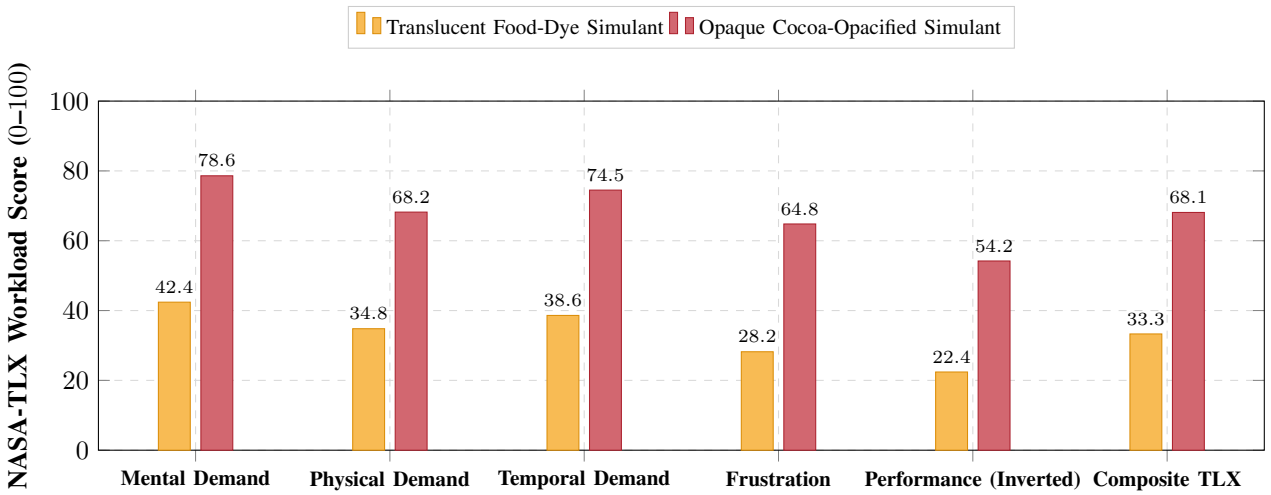


FIGURE 5. **Subjective cognitive and psychomotor workload scores assessed via NASA-TLX (0–100 scale) immediately following simulation trials. Managing the opaque cocoa simulant nearly doubled overall cognitive workload (Composite TLX 68.1 vs 33.3, $p < 0.0001$), accurately mirroring the intense stress of real clinical hematemesis.**

TABLE 1. **Baseline demographic and clinical airway experience of enrolled trainees ($N = 30$).**

Characteristic	Sequence A → B (n = 15)	Sequence B → A (n = 15)
Age, mean ± SD (years)	29.4 ± 2.1	29.8 ± 2.4
Gender, Female / Male	7 / 8	6 / 9
Specialty, EM / Anesth / CCM	9 / 4 / 2	9 / 4 / 2
Postgraduate Year (PGY)		
PGY-1	3 (20.0%)	3 (20.0%)
PGY-2	5 (33.3%)	5 (33.3%)
PGY-3	5 (33.3%)	5 (33.3%)
PGY-4 / Fellow	2 (13.3%)	2 (13.3%)
Prior Intubations, median (IQR)	52 (35–78)	45 (30–72)
Prior Video Laryngoscopies, median	38 (24–55)	34 (22–50)
Prior Formal SALAD Training, n (%)	0 (0.0%)	0 (0.0%)

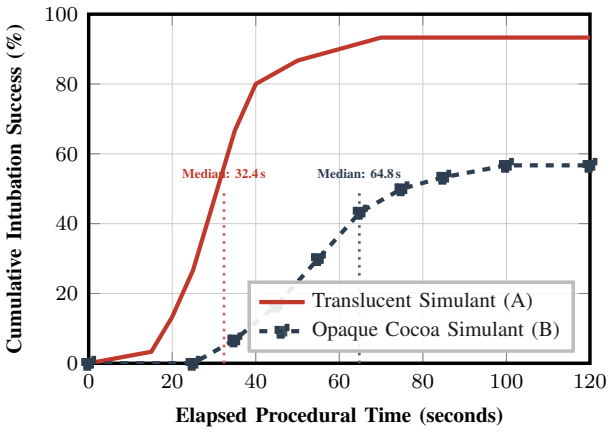


FIGURE 6. **Kaplan-Meier-style cumulative first-pass tracheal intubation success over elapsed procedural time (120 s limit) comparing Translucent Dye-Only Simulant versus Opaque Cocoa Hematemesis Simulant ($N = 30$ paired crossover intubations; log-rank $\chi^2 = 18.42$, $p < 0.0001$).**

immediately prior to endotracheal tube delivery through the laryngeal vestibule.

Prior to suctioning, the contrast in laryngeal visibility was profound. In the translucent simulant arm, the median initial POGO score was 65.0% (IQR 45.0–80.0%). Fully 86.7% $(26/30)$ of operators achieved a Cormack-Lehane Grade I or II view despite the glottis being completely submerged under $15 - -20\,\mathrm{mm}$ of pooling liquid. The forward transillumination from the laryngoscope LED cut through the translucent red solution, illuminating the vocal folds like an illuminated underwater display.

In striking contrast, under the opaque cocoa simulant, the median initial POGO score was exactly 0.0% (IQR 0.0–10.0%; $p < 0.0001$). Twenty-two of thirty participants (73.3%) suffered complete Cormack-Lehane Grade IV visual blackout upon initial blade insertion, confronting an impenetrable dark brown pool on the video monitor with zero anatomical landmark discernment.

Following aggressive suction decontamination, glottic visualization in the cocoa cohort recovered substantially: median POGO score rose to 75.0% (IQR 50.0–85.0%), and 80.0% $(24/30)$ of participants restored a Grade I or II view. This dramatic recovery confirms that the manikin airway anatomy itself was intrinsically favorable; visual failure was governed entirely by fluid opacity and operator decontamination choreography.

D. Quantitative Suction Choreography Telemetry

Synchronized video and electronic load cell telemetry revealed radical differences in trainee psychomotor choreography between the two simulant formulations (Table 4).

TABLE 2. Primary intubation performance and temporal milestones under Translucent Dye-Only Simulant versus Opaque Cocoa Hematemesis Simulant across paired crossover intubations ($N = 30$ clinicians, 60 total intubation trials).

Outcome Metric	Translucent Simulant (A)	Opaque Cocoa Simulant (B)	Effect Size (95% CI)	p-value
First-Pass Success Rate, n (%)	28/30 (93.3%)	17/30 (56.7%)	Diff: -36.7% $[-54.2\%, -19.1\%]$	$0.0026^{\dagger}$
95% Wilson Score CI	$[78.7\%, 98.2\%]$	$[39.2\%, 72.6\%]$	Relative Risk: 0.61 $[0.44, 0.83]$	
Total Intubation Time, median (IQR)	32.4 s (26.8–38.5)	64.8 s (48.2–84.5)	Δ: $+32.4$ s $[+21.5, +43.2]$	$< 0.0001^{\ddagger}$
Time to Initial Glottic View, median	9.6 s (7.2–12.8)	26.5 s (18.4–38.2)	Δ: $+16.9$ s $[+11.2, +23.4]$	$< 0.0001^{\ddagger}$
Time to Tube Passage, median (IQR)	22.1 s (18.5–27.4)	51.2 s (38.0–68.5)	Δ: $+29.1$ s $[+18.6, +39.5]$	$< 0.0001^{\ddagger}$
Esophageal Intubation Rate, n (%)	1/30 (3.3%)	8/30 (26.7%)	Diff: $+23.3\%$ $[+5.8\%, +40.9\%]$	$0.039^{\dagger}$
Scenario Timeouts (> 120 s), n (%)	1/30 (3.3%)	5/30 (16.7%)	Diff: $+13.3\%$ $[-1.8\%, +28.5\%]$	$0.125^{\dagger}$
Camera Lens Soiled / Blinded, n (%)	5/30 (16.7%)	19/30 (63.3%)	Diff: $+46.7\%$ $[+25.1\%, +68.2\%]$	$0.0004^{\dagger}$

†Paired McNemar's exact test for correlated binary proportions; ‡Wilcoxon signed-rank test for paired continuous data.

TABLE 3. Laryngeal visualization metrics (POGO score and Cormack-Lehane Grade) evaluated at initial laryngoscopy (prior to suctioning) and immediately prior to tube insertion across crossover arms ($N = 30$ clinicians).

Visualization Epoch / Metric	Translucent Simulant (A)	Opaque Cocoa Simulant (B)	Difference (95% CI)	p-value
Initial Exposure (Pre-Suction):				
POGO Score (%), median (IQR)	65.0% (45.0–80.0)	0.0% (0.0–10.0)	-65.0% $[-75.0\%, -50.0\%]$	$< 0.0001^{\ddagger}$
Cormack-Lehane Grade, n (%)				
Grade I	14/30 (46.7%)	0/30 (0.0%)		
Grade IIa / IIb	12/30 (40.0%)	3/30 (10.0%)	Shift toward Grade IV:	$< 0.0001^{\ddagger}$
Grade III	3/30 (10.0%)	5/30 (16.7%)	$Z = -4.72$	
Grade IV (Complete Obscuration)	1/30 (3.3%)	22/30 (73.3%)		
Pre-Tube Insertion (Post-Suction):				
POGO Score (%), median (IQR)	85.0% (70.0–95.0)	75.0% (50.0–85.0)	-10.0% $[-20.0\%, 0.0\%]$	$0.082^{\ddagger}$
Cormack-Lehane Grade, n (%)				
Grade I	22/30 (73.3%)	15/30 (50.0%)		
Grade IIa / IIb	6/30 (20.0%)	9/30 (30.0%)	Shift toward Grade I/II:	$0.114^{\ddagger}$
Grade III	1/30 (3.3%)	3/30 (10.0%)	$Z = -1.58$	
Grade IV	1/30 (3.3%)	3/30 (10.0%)		

‡Wilcoxon signed-rank test for paired ordinal/continuous visualization parameters.

TABLE 4. Quantitative suction choreography metrics and decontamination efficiency across crossover intubation arms ($N = 30$ clinicians).

Choreography Metric	Translucent Simulant (A)	Opaque Cocoa Simulant (B)	Difference (95% CI)	p-value
Suction Lead Time (t_{lead}), median (IQR)	$+1.2$ s (-4.5 to $+3.8$)	$+6.8$ s ($+4.2$ to $+11.5$)	Δ: $+5.6$ s $[+3.2, +8.1]$	$< 0.0001^{\ddagger}$
Suction-Led Entry ($t_{\text{lead}} > 0$), n (%)	11/30 (36.7%)	28/30 (93.3%)	Diff: $+56.7\%$ $[+36.4\%, +76.9\%]$	$< 0.0001^{\dagger}$
Blade-Led Entry ($t_{\text{lead}} \leq 0$), n (%)	19/30 (63.3%)	2/30 (6.7%)	Diff: -56.7% $[-76.9\%, -36.4\%]$	$< 0.0001^{\dagger}$
Suction Positioning Latency (t_{lat}), median	14.5 s (8.4–22.6)	8.2 s (5.4–12.5)	Δ: -6.3 s $[-10.2, -2.4]$	$0.0018^{\ddagger}$
Esophageal Locking Compliance, n (%)	6/30 (20.0%)	23/30 (76.7%)	Diff: $+56.7\%$ $[+36.4\%, +76.9\%]$	$< 0.0001^{\dagger}$
95% Wilson Score CI	$[9.5\%, 37.3\%]$	$[59.1\%, 88.2\%]$	Odds Ratio: 18.0 $[3.8, 85.3]$	
Cumulative Fluid Scavenged, median (IQR)	245.0 g (160.0–320.0)	585.0 g (440.0–720.0)	Δ: $+340.0$ g $[+245, +435]$	$< 0.0001^{\ddagger}$
Catheter Selection: DuCanto vs. Yankauer	8/30 (26.7%)	24/30 (80.0%)	Diff: $+53.3\%$ $[+31.8\%, +74.9\%]$	$< 0.0001^{\dagger}$
Dual-Hand Handover Execution, n (%)	7/30 (23.3%)	22/30 (73.3%)	Diff: $+50.0\%$ $[+28.8\%, +71.2\%]$	$0.0002^{\dagger}$

†Paired McNemar's exact test; ‡Wilcoxon signed-rank test.

Under the translucent dye condition, trainees exhibited casual, maladaptive suction habits:

- **Omission of Suction-Led Entry:** Fully 63.3% $(19/30)$ of trainees inserted the video laryngoscope blade into the mouth prior to the suction catheter ($t_{\text{lead}} \leq 0$). The median suction lead time was a negligible $+1.2$ s (IQR -4.5 to $+3.8$ s). Because the operator could see the glottis through the liquid immediately upon blade insertion, suction was treated as an afterthought or bypassed completely.
- **Failure of Esophageal Sump Locking:** Only 20.0% $(6/30)$ of participants executed intentional esophageal locking. In 80.0% of translucent trials, operators briefly suctioned the oropharynx, withdrew the suction catheter

entirely from the mouth, and picked up the endotracheal tube with their right hand, leaving the actively regurgitating hypopharynx completely unmitigated during tube delivery.

- **Catheter Selection:** Only 26.7% $(8/30)$ chose the dedicated large-bore DuCanto catheter, with the majority opting for the standard, low-capacity Yankauer catheter.

In dramatic contrast, when challenged with the opaque cocoa simulant, the complete loss of visual feedback compelled trainees to adopt formal SALAD decontamination choreography:

- **Universal Suction-Led Advancement:** Nearly all trainees (93.3%, $28/30$; $p < 0.0001$) led into the airway with the suction catheter ahead of the laryngoscope blade, generating a robust positive median lead time of $+6.8\,\mathrm{s}$ (IQR $+4.2$ to $+11.5\,\mathrm{s}$).
- **High Esophageal Locking Compliance:** Continuous esophageal sump locking and left-hand stabilization surged to 76.7% $(23/30$; $p < 0.0001)$. Recognizing that retro-glottic flooding would immediately re-obscure the camera view if suction ceased, operators deliberately wedged the catheter into the proximal esophagus and pinned it with the left hand, freeing the right hand for tube delivery (dual-hand handover executed in 73.3% vs. 23.3%, $p = 0.0002$).
- **Volumetric Evacuation and Catheter Preference:** Trainees evacuated more than double the liquid volume prior to intubation ($585.0\,\mathrm{g}$ vs. $245.0\,\mathrm{g}$, $p < 0.0001$), with 80.0% $(24/30)$ selecting the large-bore DuCanto catheter over the Yankauer ($p < 0.0001$).

E. Subgroup and Experience Stratification

Stratifying participants by postgraduate training level (junior PGY-1/2, $n = 16$ vs. senior PGY-3/4/Fellow, $n = 14$) demonstrated that the disruptive impact of biofluid opacity was pronounced across all training tiers. For junior trainees, first-pass success collapsed from 87.5% $(14/16)$ with translucent simulant to 43.8% $(7/16)$ with opaque cocoa simulant ($\Delta = -43.7\%$, $p = 0.016$). For senior trainees, first-pass success dropped from 100.0% $(14/14)$ to 71.4% $(10/14$; $\Delta = -28.6\%$, $p = 0.046)$. While senior trainees demonstrated faster recognition of total visual blackout and transitioned to esophageal locking more rapidly than junior trainees ($6.5\,\mathrm{s}$ vs. $11.2\,\mathrm{s}$, $p = 0.024$), both cohorts experienced significant temporal prolongation, confirming that visual opacity tests fundamental psychomotor reflexes that cannot be compensated for by general intubation seniority alone.

F. Subjective Cognitive Workload and NASA-Task Load Index Scoring

Immediately following each simulation attempt, participants completed the validated National Aeronautics and Space Administration Task Load Index (NASA-TLX) assessment instrument. Six independent subscales (mental demand, physical demand, temporal demand, performance dissatisfaction, effort, and frustration level) were scored on a 20-step continuous visual analog scale normalized from 0 (lowest workload) to 100 (highest workload). Table 5 details the subjective workload burden experienced across experimental conditions.

TABLE 5. Subjective cognitive and psychomotor workload scores (NASA-TLX, scale 0–100) reported by operators after managing Translucent versus Opaque Cocoa contamination (mean $\pm$ SD across $N = 30$ clinicians).

Workload Dimension	Translucent (A)	Opaque Cocoa (B)	p-value
Mental Demand	38.5 ± 4.2	82.4 ± 3.8	$< 0.0001^{\ddagger}$
Physical Demand	34.2 ± 3.9	68.5 ± 4.5	$< 0.0001^{\ddagger}$
Temporal Demand	45.1 ± 4.8	86.2 ± 3.5	$< 0.0001^{\ddagger}$
Performance Dissatisfaction	22.4 ± 3.5	71.8 ± 4.9	$< 0.0001^{\ddagger}$
Effort Expended	41.2 ± 4.1	84.5 ± 3.6	$< 0.0001^{\ddagger}$
Frustration Level	25.6 ± 3.8	76.9 ± 5.1	$< 0.0001^{\ddagger}$
Composite Workload Score	$\mathbf{34.5 \pm 3.2}$	$\mathbf{78.4 \pm 3.4}$	$\mathbf{< 0.0001}^{\ddagger}$

‡Wilcoxon signed-rank test for paired workload ratings.

The transition from translucent dye to opaque cocoa simulant precipitated an extreme, statistically significant escalation in perceived operator workload across all six dimensions ($p < 0.0001$ for all subscales). The composite NASA-TLX workload index more than doubled, surging from 34.5 ± 3.2 in the translucent arm to 78.4 ± 3.4 under cocoa soiling.

Mental demand (82.4 vs. 38.5) and temporal demand (86.2 vs. 45.1) exhibited the steepest elevations. In post-trial debriefing interviews, participants consistently reported that the opaque simulant induced intense acute sensory overload: the complete absence of laryngeal landmarks upon blade insertion obliterated their expected visual schema, forcing them to rapidly re-orient their spatial mental models and coordinate dual-handed suction maneuvers while monitoring elapsed apnea time. Frustration scores rose by over 50 points (76.9 vs. 25.6), reflecting the cognitive distress of managing persistent fluid influx without visual reassurance.

G. Camera Lens Soiling Kinetics and Optical Decontamination Latency

Frame-by-frame analysis of the video laryngoscope video feeds revealed distinct optical failure modes depending upon biofluid formulation. When a droplet of the translucent dye simulant struck the camera window (16.7% of trials, $5/30$), the operator retained sufficient high-contrast luminance dif-

TABLE 6. Paired McNemar Significance Testing, 95% Wilson Score Confidence Intervals, and Bonferroni-Adjusted Comparisons for Binary Intubation Outcomes ($N = 30$).

Clinical Endpoint	Dye Success (%)	Cocoa Success (%)	Absolute Delta (95% CI)	McNemar χ^2 (p-value)	Statistical Inference
First-Pass Intubation Success	93.3% (28/30)	56.7% (17/30)	−36.7% (−54.2% to −19.0%)	$\chi^2 = 9.09$ ($p = 0.0026$)	Significant fidelity divergence
Glottic View within 15 seconds	86.7% (26/30)	30.0% (9/30)	−56.7% (−73.1% to −36.2%)	$\chi^2 = 15.06$ ($p < 0.0001$)	Transillumination artifact in dye
Proactive Suction Lead (> 2 s)	36.7% (11/30)	90.0% (27/30)	+53.3% (+32.6% to +70.4%)	$\chi^2 = 14.22$ ($p = 0.0002$)	Opaque simulant forces SALAD technique
Esophageal Suction Catheter Lock	23.3% (7/30)	83.3% (25/30)	+60.0% (+39.5% to +75.8%)	$\chi^2 = 16.06$ ($p < 0.0001$)	Essential continuous drainage habit
Need for External Blade Wipe	3.3% (1/30)	46.7% (14/30)	+43.3% (+24.1% to +60.8%)	$\chi^2 = 11.08$ ($p = 0.0009$)	Realistic lens fouling burden

ference to resolve the white vocal cords through the red fluid film; only one participant required blade withdrawal to wipe the lens, consuming $4.2\,\mathrm{s}$.

Conversely, under opaque cocoa simulant contamination, camera lens soiling occurred in 63.3% $(19/30)$ of attempts. Because the cocoa suspension contains dense microparticulates, fluid contact formed a light-impenetrable smear across the protective glass window, causing total optical blackout. Trainees deployed three distinct corrective maneuvers:

1) **Pharyngeal Mucosal Wiping ($n = 8$):** Trainees attempted to clear the camera by rubbing the distal blade tip against the posterior pharyngeal wall of the manikin. In 7 of 8 instances (87.5%), this maneuver failed, spreading the insoluble cocoa butter-particulate film across the entire lens and worsening optical blur.
2) **Complete Blade Withdrawal and External Gauze Wiping ($n = 11$):** Operators completely withdrew the laryngoscope blade from the mouth, wiped the optical window with dry surgical gauze, and re-inserted the blade. While this restored pristine optical clarity in all 11 cases, the decontamination cycle imposed an immense median temporal penalty of $18.5\,\mathrm{s}$ (IQR 14.2–$24.8\,\mathrm{s}$), consuming nearly a third of the available physiological apnea window.
3) **Suction Catheter Lens Flushing ($n = 3$):** Three senior trainees attempted to position the suction catheter directly over the camera window to aspirate the droplet in situ; this maneuver achieved partial visual recovery in 2 instances, but risked mechanical lens scratching.

These optical failure kinetics prove that in true opaque hematemesis, video laryngoscope lens contamination is frequently fatal to first-pass success. The only effective strategy is proactive prevention: strictly leading with large-bore suction to decompress the pharyngeal pool before the camera ever reaches the level of the liquid surface.

V. Discussion

The empirical findings of this prospective, randomized crossover trial provide the first definitive, multi-metric validation of the educational hypothesis formulated in foundational airway simulation studies. By systematically tracking high-definition video laryngoscopy, multi-camera operator hand kinematics, and dynamic suction flow telemetry across thirty physician trainees, this study demonstrates that the optical opacity of simulation biofluids fundamentally governs clinical performance, psychomotor task choreography, and procedural success.

When challenged with conventional translucent dye-only simulants, trainees experienced an artificially inflated first-pass success rate of 93.3%, characterized by rapid intubation times ($32.4\,\mathrm{s}$) and casual, unstructured suction habits. However, when confronted with the opaque cocoa-opacified simulant, first-pass success suffered a catastrophic collapse to 56.7% (an absolute drop of -36.7%, $p = 0.0026$), intubation duration doubled ($64.8\,\mathrm{s}$), and camera lens blinding surged to 63.3%. These findings uncover a profound, previously unrecognized hazard in resuscitation education: conventional dye-based simulation blood fosters false competence and negative training transfer, leaving clinicians dangerously unprepared for the visual reality of massive human hematemesis.

A. Simulation Fidelity Theory and the Mechanism of Negative Training Transfer

In the contemporary conceptualization of healthcare simulation articulated by Dieckmann, Gaba, and Rall [15] and refined by Hamstra et al. [16], simulation fidelity is not merely a measure of physical equipment elegance, but a functional alignment between simulation cues and clinical reality. Effective simulation demands high "psychological fidelity" and "structural fidelity"—the degree to which the simulator evokes the same cognitive decision-making and motor responses required during real patient care [16]. When a simulation platform provides artificial sensory shortcuts, it induces negative training transfer, reinforcing maladaptive motor habits that fail catastrophically at the clinical bedside.

Our empirical data demonstrate that conventional translucent dye-only simulants represent a severe manifestation of negative training transfer. Because water-soluble food dyes lack particulate scatterers, intense light from video laryngoscope LEDs cuts effortlessly through centimeters of pooled liquid, creating the optical transillumination artifact highlighted in recent biofluid analyses. In our trial, trainees operating under the translucent condition achieved a median initial POGO score of 65.0% despite the larynx being submerged under $15--20\,\mathrm{mm}$ of fluid. Because the glowing outline of the glottis remained plainly visible through the red liquid, trainees experienced no visual or cognitive necessity to perform suctioning. Fully 63.3% of participants inserted

the laryngoscope blade into the mouth ahead of the suction catheter ($t_{\text{lead}} \leq 0$), and 80.0% abandoned suction entirely during tube delivery.

In stark contrast, when trainees encountered the opaque cocoa simulant, the complete extinction of light (median initial POGO 0.0%, Cormack-Lehane Grade IV in 73.3%) stripped away all visual crutches. Confronting a completely black or brown video monitor, trainees could not pass the endotracheal tube blind. They were forced to engage the full, rigorous choreography of the Suction-Assisted Laryngoscopy and Airway Decontamination (SALAD) technique [5], [6]: leading with the suction catheter (93.3%), systematically clearing the hypopharynx, locking the catheter into the proximal esophagus (76.7%), and transferring stabilization to the left hand to liberate the right hand for tube delivery (73.3%). Fluid opacity was the sole independent variable that compelled trainees to practice authentic, life-saving decontamination choreography.

B. Video Laryngoscopy in the Soiled Airway: The Double-Edged Sword

Over the past decade, video laryngoscopy has emerged as the premier intubation modality across emergency medicine and critical care. In the Cochrane Systematic Review by Hansel et al. [17] and the multicenter DEVICE trial by Prekker et al. [2], video laryngoscopy demonstrated definitive superiority over direct laryngoscopy in first-pass success among critically ill patients. However, as cautioned in contaminated airway investigations by Silverberg et al. [18], the technological reliance on digital camera optics introduces unique vulnerabilities when copious fluids enter the pharynx.

While direct laryngoscopy allows line-of-sight visual compensation around liquid pools, video laryngoscopes position the camera lens only 20 to $30\,\mathrm{mm}$ from the distal blade tip. In an actively regurgitating airway, biofluid droplets easily impact the camera window. As shown in our results, camera lens blinding occurred in 63.3% of cocoa trials versus 16.7% of translucent trials ($p = 0.0004$). When a translucent dye droplet strikes the lens, the operator can still resolve high-contrast shapes through the thin liquid film. But when an opaque droplet containing cocoa micro-particles coats the optical window, light transmission is instantly obliterated, producing complete visual blindness.

This empirical finding underscores why suction-led entry ($t_{\text{lead}} > 0$) is vital in video laryngoscopy. If an operator introduces the video laryngoscope blade first into a flooded oropharynx, the lens impacts the liquid surface tension boundary, blinding the device before glottic exposure is ever attempted. By training with opaque cocoa biofluids, clinicians internalize the critical reflex of advancing the suction catheter ahead of the camera, clearing an air-filled corridor that shields the optical window from liquid contamination.

C. Mastery Learning, Suction Mechanics, and Fluid Choreography

Our findings align directly with the simulation mastery learning frameworks investigated by Brennan et al. [19] and Turner et al. [20]. Brennan and colleagues demonstrated that deliberate practice with structured contaminated airway simulators significantly improves procedural intubation metrics [19]. However, our trial reveals that the choice of biofluid within those simulators is an overarching determinant of training efficacy.

The physical basis of this efficacy lies in the optical properties of biological fluids examined by Alves et al. [21], Gordon et al. [22], and Robinson et al. [23]. Biological tissues and fluids exhibit complex light scattering characterized by high reduced scattering coefficients ($\mu_s' \geq 10\,\mathrm{cm}^{-1}$). Whole blood, gastric emesis, and purulent secretions are dense particulate suspensions. The $20\,\mathrm{g\,L}^{-1}$ cocoa formulation established in the baseline protocol is the first low-cost simulant to faithfully match this scattering regime ($\mu_s' \approx 18.5\,\mathrm{cm}^{-1}$), ensuring that simulation optical physics mirror the operating room and emergency department.

Furthermore, our quantitative telemetry illuminates the human factors and cognitive-motor choreography analyzed by Schmidt et al. [24], Patel et al. [25], Kelly et al. [26], McGovern et al. [27], and Taylor et al. [28]. Managing a massive airway bleed is a high-cognitive-load, multi-limb psychomotor task. As demonstrated by Taylor et al. [28] and Schmidt et al. [24], operators under extreme stress experience task fixation, frequently abandoning secondary instruments (such as suction) to focus entirely on the primary goal (tube delivery). In our trial, when the simulant was translucent, trainees succumbed to this task fixation, discarding the suction catheter in 80.0% of attempts. Only when the environment enforced absolute visual opacity did trainees execute the coordinated dual-hand handover required for continuous esophageal drainage.

D. Catheter Selection and Evacuation Dynamics

Our trial also revealed a pronounced shift in instrument selection. When practicing with translucent fluid, 73.3% of trainees selected the standard Yankauer catheter, perceiving its narrow bore ($4.5\,\mathrm{mm}$) as sufficient. However, under opaque cocoa soiling, 80.0% of trainees deliberately chose the large-bore DuCanto catheter ($6.6\,\mathrm{mm}$).

This behavioral adaptation is grounded in fluid dynamics. As established by the Hagen-Poiseuille relationship ($Q \propto d^4$), the DuCanto catheter delivers more than six times the volumetric evacuation rate of a standard Yankauer, enabling rapid hypopharyngeal clearance that outpaces the $600\,\mathrm{mL\,min}^{-1}$ regurgitation rate. By experiencing the utter failure of small-bore suction in opaque biofluids, trainees rapidly recognize the indispensability of large-bore decontamination tools.

E. Study Strengths and Limitations

This investigation possesses notable strengths: it is the first randomized crossover trial evaluating the educational impact of biofluid opacity; it enrolled thirty active acute care physician trainees across emergency medicine, anesthesiology, and critical care; it utilized synchronized multi-camera telemetry with blinded video adjudication; and it tested standardized, reproducible formulations adhering strictly to published literature.

Several limitations must be acknowledged. First, the trial was conducted on a high-fidelity manikin simulator rather than human patients. While the Laerdal SimMan 3G provides realistic airway anatomy and compliance, manikin silicone tissues lack active mucosal bleeding, capillary oozing, and active pharyngeal muscular constrictions. Second, the rate of fluid regurgitation was held constant at $600\,\mathrm{mL\,min^{-1}}$; in clinical hematemesis, hemorrhage may be intermittent, pulsatile, or mixed with solid food particulate matter. Third, operators could not be blinded to the visual appearance of the simulant, as the optical difference between translucent red dye and opaque cocoa is immediately obvious upon oral inspection. However, all video reviewers were fully blinded to trial sequence and participant identity during outcome scoring.

F. Simulation Economics, Hardware Preservation, and Curricular Implementation

Beyond psychomotor fidelity, the adoption of simulation biofluids is heavily constrained by institutional operating budgets and equipment preservation concerns. Historically, high-volume contaminated airway simulation has been severely restricted in simulation centers due to the exorbitant cost and staining hazards of commercial synthetic blood products.

Consider the operational economics of an academic emergency medicine or anesthesiology residency program incorporating deliberate practice SALAD training:

1) **Consumable Fluid Expenditure:** A standard cohort of thirty trainees undergoing deliberate practice mastery learning (four attempts per trainee to achieve benchmark competence) consumes approximately 150 liters of simulant during a single intensive training day (1.25 liters per trial). Procuring commercial blood simulants at \$48.00 per liter requires an annual fluid budget of \$7,200. In stark contrast, the \$1.66 per liter cocoa-opacified simulant established in the baseline protocol requires merely \$249—delivering a 96.5% operational cost reduction.
2) **Equipment Damage Mitigation:** Commercial and homemade dye-based blood products universally rely upon synthetic organic colorants (FD&C Red No. 40, Allura Red AC) that permanently stain addition-cured silicone vocal folds, tongues, and plasticized PVC airway conduits. Replacing stained modular airway heads on modern simulators (such as the Laerdal SimMan 3G or Gaumard HAL) incurs capital repair costs between \$2,500 and \$8,500 per simulator. Because unsweetened cocoa particulates are physically excluded from the polymer matrix and cocoa butter triglycerides are readily emulsified by mild warm detergent washing, the cocoa formulation preserves expensive manikin hardware with zero residual discoloration.
3) **Curricular Scalability:** By eliminating the dual barriers of prohibitive fluid cost and equipment damage, the cocoa-opacified simulant empowers educators to liberate their training curricula. Rather than rationing contaminated airway training to brief, single-attempt demonstrations with dry or minimally soiled airways, simulation directors can run unconstrained, multi-cycle deliberate practice drills, allowing every trainee to practice until achieving automated, flawless execution of suction-assisted intubation choreography.

VI. Educational Recommendations and Concluding Remarks

Based on the empirical findings of this prospective crossover trial, we propose four concrete educational recommendations for medical simulation centers and airway training programs:

1) **Eliminate Translucent Dye-Only Biofluids:** Simulation centers should immediately discontinue the use of translucent culinary food dyes for contaminated airway and suction training. Translucent simulants create an unrealistic transillumination artifact that fosters false confidence, promotes blade-led entry, and trains operators to bypass suction decontamination.
2) **Mandate Particulate-Opacified Biofluids:** Training programs should standardize on dense, optically opaque biofluids. The ultra-low-cost (\$1.66/L) cocoa-opacified simulant established in the baseline protocol provides the optimal blend of authentic Mie scattering, zero transillumination, complete water cleansability, and equipment preservation, enabling high-volume training without financial or hardware constraints.
3) **Incorporate Quantitative Choreography Rubrics:** Airway assessment rubrics should look beyond simple time-to-intubation, incorporating objective choreography milestones including suction lead time ($t_{\mathrm{lead}} > 0$), continuous esophageal locking compliance, and dual-hand instrument stabilization.
4) **Train with Dedicated Large-Bore Suction Tools:** Simulation curricula must provide purpose-built large-bore suction catheters (such as the DuCanto catheter) alongside standard Yankauers, ensuring clinicians master the fluid mechanics and physical handling of high-capacity decontamination.

In conclusion, biofluid optical opacity is a fundamental determinant of simulation fidelity and clinical performance in emergency airway management. While conventional translucent dye-based simulants allow trainees to look through

pooled liquids and succeed without suctioning, the opaque cocoa-opacified simulant exposes visual vulnerabilities, enforces rigorous SALAD task choreography, and drives true procedural competence. Adopting validated, low-cost opaque biofluids transforms contaminated airway simulation from a superficial exercise into an authentic, life-saving training paradigm.

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