IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 18 July 2023, accepted 30 July 2023, date of publication 10 August 2023, date of current version 17 August 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3303925

RESEARCH ARTICLE

Development of a Low-Intensity Light Imaging Probe for Childbirth Cervical Dilation Image Acquisition

TEMITOPE O. TAKPOR[1,2], (Graduate Student Member, IEEE), ADEREMI A. ATAYERO[2], (Member, IEEE), EMMANUEL ADETIBA[1,3,4], (Member, IEEE), AND JOKE A. BADEJO[2,3], (Member, IEEE)

[1]Department of Electrical and Information Engineering, Covenant University, Ota 112233, Nigeria
[2]IoT-Enabled Smart and Connected Communities (SmartCU) Research Cluster, Covenant University, Ota 112233, Nigeria
[3]Covenant Applied Informatics and Communication Africa Center of Excellence, Covenant University, Ota 112233, Nigeria
[4]HRA, Institute for Systems Science, Durban University of Technology, Durban 4001, South Africa

Corresponding author: Temitope O. Takpor (temitope.takpor@covenantuniversity.edu.ng)

This work was supported in part by the Covenant University Centre for Research, Innovation and Discovery (CUCRID); in part by General Electric (GE) Garage, Lagos Office; in part by the Department of Biological Sciences, Covenant University; in part by the Department of Mechanical Engineering, Covenant University; and in part by the Nigerian Institute of Marine Oceanography, Lagos.

ABSTRACT Cervical dilation is the most important parameter that is assessed during childbirth to validate that a woman is truly in labour and whether labour is progressing as expected. It is the opening of a mother's cervix from when it is closed at 0 cm to when it is fully dilated at 10 cm, for the baby to pass through and be delivered. The cervix is a cylinder-shaped tissue that connects the uterus to the vagina. Cervical dilation is majorly assessed through a highly subjective, painful, error-prone, and infection-prone Vaginal Examination method. The method involves a doctor or midwife wearing sterilized gloves and inserting his or her fingers through the vagina to manually assess cervical dilation and mentally visualize it. Hence, in this research, a prototype of a novel low-intensity light imaging probe was developed to acquire images of cervical dilation simulation models for further processing and analysis. The probe was designed with 3D computer-aided design software. Finite element analysis was carried out on the design before it was rapid prototyped. Then, a camera and a light source were inserted into the probe to capture 2,880 cervical dilation images in low-light intensities of 28 Lux and 50 Lux, due to the penetration depth of bright light intensity and heat into tissues. Image preprocessing was carried out on the images by applying a low-light image enhancement technique. This research demonstrated the use of a low-intensity light imaging probe as a possible objective alternative to the subjective insertion of fingers in vaginal examination.

INDEX TERMS Cervical dilation, computer-aided design, medical imaging, medical image processing, low-light image enhancement.

I. INTRODUCTION

In obstetrician practice, improving the quality of care and assessing vital parameters during pregnancy, childbirth, and the immediate postnatal period have been identified as impactful strategies for preventing and reducing maternal deaths [1], [2], [3]. Quality of care during childbirth involves access to quality obstetric emergency care, availability of skilled obstetric workforce, strengthening of health systems and services, investments in health systems and technologies, quality training of midwives, doctors, and health workers, inter-professional and multi-disciplinary collaboration, and innovative leadership and governance initiatives [4], [5], [6], [7], [8].

Development and deployment of innovative childbirth monitoring systems and devices will enhance the early

The associate editor coordinating the review of this manuscript and approving it for publication was Santosh Kumar.

detection and treatment of labour complications and fetal distresses [3], [9], [10]. Childbirth monitoring usually involves labour progression monitoring, maternal condition monitoring, and fetal condition monitoring [10]. Some studies reported that there is an urgent need for more research on new methods of assessing childbirth progression parameters [9], [11], [12]. The parameters influence clinical decisions made by midwives and doctors in managing the well-being of a mother and her baby during childbirth [13]. They include cervical dilation, cervical effacement, cervical softness, uterine contractions, fetal heart rate, fetal head station, progression angle, and appearance and behavior of the mother [10], [14], [15], [16], [17]. Of all the parameters, cervical dilation is the most important and gold standard parameter because it informs the midwives and doctors when labour truly starts, and whether labour is progressing as expected [11], [12], [18], [19], [20]. Cervical dilation is also one of the key factors in predicting the type of delivery (either vaginal birth or caesarean section). It can be used to predict and detect preterm (premature) birth in high-risk women [21], [22].

Cervical dilation is the natural opening of the mother's cervix from 0 cm to 10 cm for the baby to pass through during vaginal delivery [23]. The cervix is a tissue that connects the uterus (womb) to the vagina. Throughout pregnancy the cervix remains closed until the period of labour. Then it softens, and dilates from 0 cm (no dilation at all) to 10 cm (full dilation). Cervical Dilation is majorly assessed through a highly subjective and painful Vaginal Examination (VE) method [14], [24], [25], [26]. The method involves a midwife or doctor gaining access to the cervix through the vagina opening, by wearing sterilized gloves and inserting his/her fingers to feel the cervix, mentally visualizing it, and assess how dilated it is [14], [27], [28]. Vaginal examination is error-prone, infection-prone, inconsistent, irreproducible, uncomfortable, painful and highly subjective [20], [25]. Reports show that some women view this method as abusive, embarrassing, emotionally traumatic, privacy-invasive, and dishonorable particularly in prolonged labour where different medical personnel have to examine the woman [9], [25], [26], [29]. The results of cervical dilation using the vaginal examination method are influenced by the experience and finger size of the examiner [20], [30], [31], [32], [33]. Infections such as endometritis and chorioamnionitis can be introduced to the womb and the baby during vaginal examination, particularly in low-income countries where disposable gloves and disinfectants might not be readily accessible [9], [17], [19], [34], [35]. Infections are reported to be one of the major causes of maternal mortality [36], [37], [38].

Evidence has shown that intrapartum ultrasound (labour ultrasound) imaging could be a possible alternative to vaginal examination, but there are limitations to this method [20], [24], [34], [39], [40], [41]. It is the most explored imaging method for cervical dilation assessment [10], [39]. Its limitations are difficulty in assessing dilation when membranes (amniotic sac of the baby) are ruptured; reduced ability to assess dilation when dilation is greater than or equal to 8cm; poor visualization of the cervix; high dependency on the operator; and high cost of ultrasound equipment [24], [31], [34], [41], [42], [43].

Moreover, other methods such as mechanical, electromechanical and electromagnetic cervimeters that were developed and tested, were unsuitable for cervical dilation assessment clinically [31], [44]. The shortcomings of the cervimeters were discontinuity of readings, lack of displays and recording devices, high invasiveness, and heavy structures that interfere with cervical dilation [19], [45]. Also, electronic devices that were developed were not applicable [31]. There were difficulties in attaching the sensor to the appropriate area of the cervix [33]. Especially at full cervical dilation (10cm), the sensor could not be placed on the cervix because the cervix was inaccessible due to the baby's protruding head [14], [31]. Recent studies stated that suitable devices have not yet been developed for cervical dilation assessment [19], [20], [46].

Over the years, comprehensive images of the body organs, tissues, and cells have been obtained for medical diagnosis and treatment through different medical image acquisition methods such as X-ray, Ultrasound Imaging, Magnetic Resonance Imaging (MRI), Computerized Tomography (CT), Optical Imaging, and Nuclear Medicine Imaging [47].With rapid advances in optical imaging methods, high-resolution images have been acquired to provide detailed information for medical personnel. Optical imaging is a powerful, attractive, and noninvasive technique that uses non-ionizing radiation such as visible light, infrared light and ultraviolet light [48], [49], [50]. It is exceptionally useful for visualizing tissues. The visible light spectrum is from 400 nm to 700 nm, and it is used to produce visible images in biomedical applications such as endoscopy and microscopy [51]. While the ultraviolet light spectrum is from 10 nm to 400 nm, and the infrared light spectrum is from 700 nm to 1 mm. They are usually used for fluorescence and multispectral imaging applications [51]. The simplest and most extensively used method of optical imaging is endoscopy [50]. It uses an endoscope, which is a flexible tube system with a light source (for illumination) and a camera to view and capture an organ or a tissue. Endoscopy gives a better image quality than ultrasound method [50], [52]. There are different types of endoscopy methods depending on the specific application.

The principal drawback of optical imaging is the penetration depth of bright light intensity and heat into the tissues [48], [53]. A study reported that imaging methods for monitoring cervical dilation are limited due to the unascertained effect it may have on the baby [9]. However, this research investigated the light intensity of a bioluminescent light source because of its natural production of cool dim light (low-light intensity) with little or no heat [54]. Bioluminescence is a natural source of light that occurs as a result of a chemical reaction (light-emitting molecule and enzyme) in living organisms such as fireflies and bioluminescent

bacteria. It has been reported that less than 1% of its energy is emitted as heat, and the rest as visible light [54]. A company named Glowee in France invented a Biolighting living system using bioluminescent bacteria (that glows in the dark) as a light source () [55].

Furthermore, medical image processing is required after imaging has been carried out to improve image visibility, extract valuable information for analysis, and provide objective medical diagnosis [47], [56], [57]. Hence, the aim of this research is to develop a low-intensity light imaging probe for cervical dilation image acquisition. The images acquired would be processed for better image visibility.

II. OPTICAL IMAGING OF THE CERVIX

The endoscopy method that is used for the optical imaging of the cervix is called colposcopy. The colposcopy method uses colposcope devices and other similar optical imaging devices in visualizing and acquiring high-resolution images of the cervix for effective cervical cancer diagnosis, after a pap smear [58], [59], [60]. Optical imaging has revolutionized the visualization of lesions [60]. The colposcope devices usually have a camera and a light source for image or video acquisition. They are connected to a computer for real-time visualization. The light source could either be Light Emitting Diodes (LEDs), laser light, or halogen light [61]. The light source functions at bright light intensities of 2,800 Lux to 24,000 Lux to detect precancerous lesions of the cervix [62], [63]. The surface of the cervix is normally scanned with ultraviolet or white light, then fluorescent and reflected light patterns produced by the cervical tissue are collected and analyzed [64]. In recent times, the colposcope devices are designed to be compact and mobile for easy access at point-of-care locations [65].

A. DEVICES FOR OPTICAL IMAGING OF THE CERVIX

1) POINT-OF-CARE TAMPON (POCKET) COLPOSCOPE

The low-cost ultra-portable Pocket Colposcope was designed by Lam et al. [61], [64], [66], [67], [68]. The Colposcope has a unique shape of a tampon which is a product that is inserted into the vagina during the monthly menstruation cycle to absorb the menstrual blood. The Colposcope can be inserted into the vagina and positioned at 3cm to 4cm away from the cervix like a transvaginal ultrasound probe to capture images of the cervix for cervical screening in limited-resource settings [66]. It consists of 5-megapixel (MP) Complementary Metal-Oxide-Semiconductor (CMOS) camera, and a concentric ring of white and green Light-Emitting Diodes (LEDs) for higher image quality [61], [68]. It has a light intensity range of 2800 lux to 20,000 lux, which is similar to the light intensity range (3000 lux to 24,000 lux) of standard digital colposcopes that are used in high resource settings [63].

2) CALLASCOPE

It is a speculum-free imaging tool designed by Asiedu et al. for the visualization of the female lower reproductive system [64], [66], [67], [68]. It was designed to completely avoid the use of a speculum because it creates pain, discomfort, fear and embarrassment to women that undergo cervical cancer screening [66], [69]. A speculum is usually used with a colposcope. The Callascope was designed with an introducer (vaginal inserter) as an alternative to the speculum. The introducer has a tip shaped as a Calla Lily, which is the novelty in the Callascope that allows a speculum-free cervix visualization [69]. The Callascope was designed to have a 2-megapixel or 5-megapixel CMOS camera with a lens and a concentric ring of white LEDs [69].

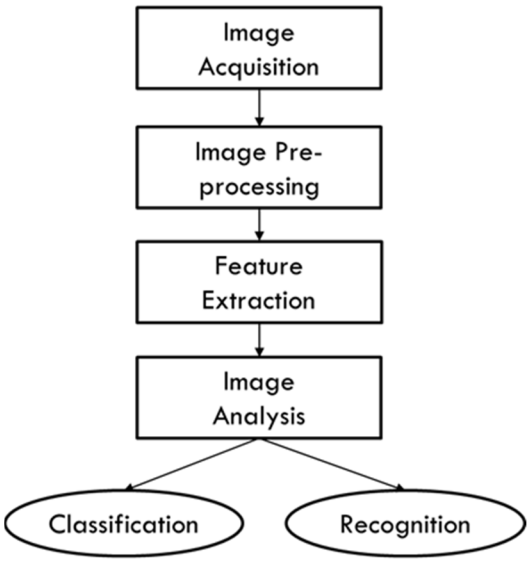

FIGURE 1. Generic block diagram for medical image processing.

3) SMARTPHONE MICROENDOSCOPY

It was designed by Hong et al. to capture high resolution fluorescence images for detecting pre-cancerous lesions of the cervix and internal organs [70]. This system consists of a fiber optic imaging bundle, a smartphone with a rear camera and a blue LED with condenser lens [70].

4) DUAL MODAL FLUORESCENT COLPOSCOPE

It was designed by Wang et al. for visible light imaging and NIR (near infrared) fluorescent imaging of the cervix [71]. It consists of a Charged-Couple Device (CCD) camera, and white LEDs for visible light imaging. The excitation light source that was used for the fluorescent imaging included four NIR laser diodes.

III. MEDICAL IMAGE PROCESSING

Advances in medical image processing have increased accuracy and robustness of medical image analysis, which has helped to greatly improve medical diagnosis [56], [72]. The generic stages of medical image processing involve image acquisition, image preprocessing, feature extraction, and image analysis (image recognition or image classification) as demonstrated in Fig. 1.

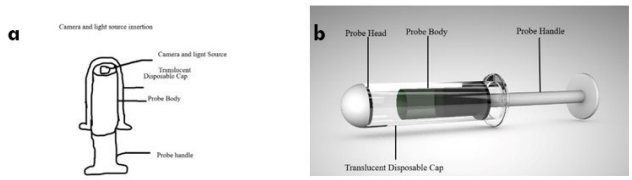

FIGURE 2. (a) Sketch of the light imaging probe; (b) Graphics design of the light imaging probe.

Image acquisition involves the transformation of a real-world image into a cluster of numerical data [73]. The process of image acquisition is fully dependent on a hardware device or system. It is achieved by a suitable camera and light for a specific application. The acquired images are preprocessed before feature extraction and image analysis.

Image preprocessing involves image filtering, image enhancement, noise reduction, geometric transformations, and image registration. Image filtering and enhancement are usually one of the initial phases of image preprocessing [74]. It is the process of adjusting or modifying images, and removing noise to give a more suitable and enhanced quality image for further image analysis. Image enhancement techniques include histogram equalization, contrast adjustment and decorrelation stretching, which are used for contrast enhancement. Furthermore, images that are captured in low-light or poor lighting conditions can have their visibility improved through low-light image enhancement techniques such as dehazing algorithm (haze removal technique), histogram equalization, and deep learning-based algorithms (LLNET – Low-light Enhancement Network).

IV. MATERIALS AND METHODS

The research methodology of this research comprises of three stages which include design and development of low-intensity light imaging probe, image acquisition phase, and image preprocessing phase.

A. DESIGN AND DEVELOPMENT OF A LOW-INTENSITY LIGHT IMAGING PROBE

A light imaging probe was designed and developed to acquire images of cervical dilation simulation models, and further processing was carried out on the images. The novel design of the probe was inspired and shaped in a similar way to a female SpeediCath® catheter (manufactured by Coloplast), and a prefilled syringe.

The sketch of the light imaging probe is shown in Fig. 2a, and the graphics illustration design is shown in Fig. 2b.

1) THREE-DIMENSIONAL (3D) COMPUTER-AIDED DESIGN (CAD) OF THE LIGHT IMAGING PROBE

The light imaging probe was designed with SOLIDWORKS 3D CAD software tool as shown in Fig. 3. The 3D probe design was generated in SLDPRT (SolidWorks Part) file format. The probe comprises of four compartments as shown in Fig. 4. The compartments include a translucent disposable tube cap, a probe head, a hollow probe body, and a plunger probe handle. The head of the probe is detachable. The body of the probe has a hollow for the insertion of a camera and a light source. The dimensions of the probe are shown in Fig. 5. The length and breadth of the probe are 230mm and 58mm, respectively. These dimensions were based on the dimensions of a standard transvaginal ultrasound probe (approximately 340mm × 60mm), and the sizes of the camera and LED light source that were used in this research.

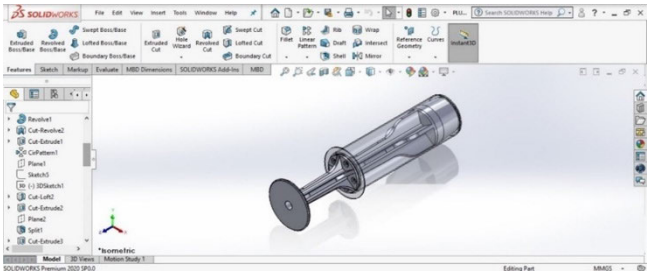

FIGURE 3. 3D CAD probe design.

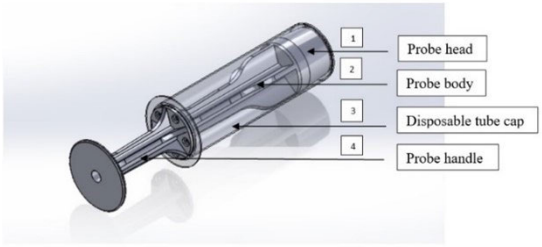

FIGURE 4. Design overview of probe.

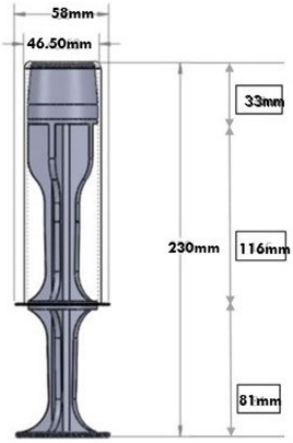

FIGURE 5. Dimensions of probe design.

2) FINITE ELEMENT ANALYSIS

The Finite Element Analysis (FEA) simulation of the probe design was carried out with the SOLIDWORKS 3D CAD software tool. The type of FEA that was conducted is the static stress analysis, in order to test the stress load

TABLE 1. Properties of the probe design for static stress analysis.

Model	Volumetric Properties	Material Properties	
Solid Body (Plunger Static Stress Analysis)	Mass: 0.12117 kg	Name:	PLA Plastics
		Model type:	Linear Elastic Isotropic
	Volume: 0.00011431 1 m^3	Default failure criterion:	Max von Mises Stress
		Yield strength:	2e+07 N/m^2
	Density: 1,060 kg/m^3	Tensile strength:	2.96e+07 N/m^2
		Elastic modulus:	2.24e+09 N/m^2
	Weight: 1.18747 N	Poisson's ratio:	0.38
		Mass density:	1,060 kg/m^3
		Thermal expansion coefficient:	8.57e-05 /Kelvin

TABLE 2. Load details exerted on the probe design for static stress analysis.

Load Name	Volumetric Properties	Material Properties	
Pressure-1		Entities:	3 face(s)
		Type:	Normal to selected face
		Value:	1,470.96
		Units:	N/m^2
		Phase Angle:	0
		Units:	deg
		Entities:	3 face(s)
		Type:	Normal to selected face
		Value:	1,470.96

distribution and strain on the probe design. The load (pressure) applied to the probe design during the static stress analysis was 15cm H20 (1470.96 Pa), as used by Asiedu et al. in the analysis of a colposcope vaginal inserter [68]. The pressure used is slightly higher than the vaginal pressures of a woman in a supine position (lying horizontally with face and torso facing up) [68]. Table. 1 displays the properties of the probe design, and Table. 2 displays the load details.

3) 3D PRINITING OF THE PROBE

The 3D CAD probe design was rapid prototyped with MakerBot 3D Printer which uses FDM technology. The 3D printing process that was carried out is shown in Fig. 6.

The available raw material that was used for the 3D printing was a Poly Lactic Acid (PLA) filament, which is

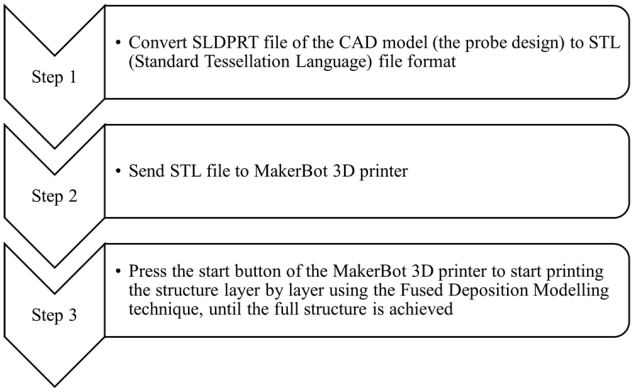

FIGURE 6. 3D printing process.

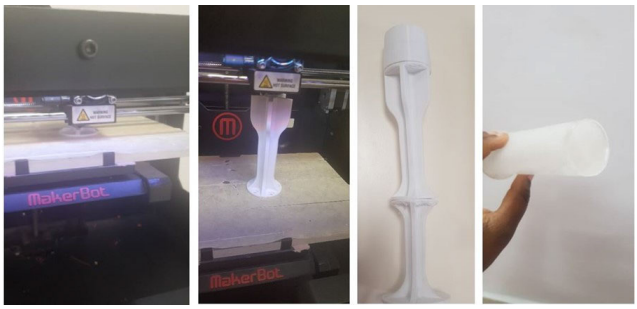

FIGURE 7. Stages of the 3D printed probe prototype.

commonly used in FDM technology. PLA is considered as the best filament for the FDM 3D printing because it offers a high dimensional accuracy, great aesthetic appeal, widely available, the rate of contraction is less in comparison to others, and it is perfect for creating a prototype of any kind [75], [76], [77]. The PLA was inserted into the nozzle of the MakerBot FDM printer, and the probe design was printed under the fused deposition modelling method. Fig. 7 shows the stages of the 3D printed probe prototype. FDM was used in this research because SLA and SLS are very expensive. The 3D CAD design and 3D printing were both carried out at General Electric (GE) Garage, Victoria Island, Lagos, Nigeria. The PLA filament was used to print the probe head, hollow probe body, and plunger probe handle. A Polyethylene terephthalate glycol (PETG) filament, which is a thermoplastic polyester was used to print the translucent disposable tube cap due to its translucent characteristic feature [78]. The PET is what is commonly used for plastic water bottles [79]. Then, a clear acrylic disc was used to cover the surface of the disposable tube cap.

4) ELECTRONIC AND OPTICAL SETUP

A Basler acA1440-220uc area scan camera was used as the camera of the light imaging probe. The camera had a Sony IMX273 CMOS sensor that delivers 227 frames per second. Basler is a global manufacturer of machine vision cameras, offering different types of digital cameras with great color fidelity, high dynamic range and light sensitivity [80]. The

FIGURE 8. Plates of bioluminescent vibrio fischeri bacteria and photobacterium broth.

FIGURE 9. Camera and lens mounted on the probe body with LED light source attached.

FIGURE 10. (a) Fetal monitoring and labour progress model set; (b) Nine cervical dilation simulation models.

FIGURE 11. Labelled cervical dilation simulation models.

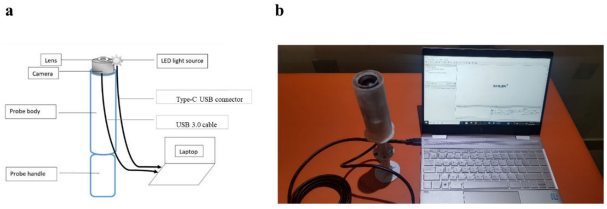

FIGURE 12. (a) Schematic diagram of light imaging probe setup; (b) Light imaging probe setup.

camera has a housing size of 29.3 mm × 29 mm × 29 mm (L × W × H). It has a USB 3.0 cable that interfaces to a phone, tablet, or computer for power supply, image capture and image transfers. The camera was used with a Basler premium lens C125-0418 of 4.0mm focal length, F- stop settings from F1.8 – F22, and 5MP resolution.

A white LED-based endoscope was used as the light source of the light imaging probe. It has 6 white LEDs arrayed together, and an adjustable knob to switch on the light and tune it to different light intensities. The dimensions of the white LED-based endoscope are 7.87 × 3.94 × 1.18 inches (L x W x H). It has 3 types of USB connectors that can be plugged into a mobile phone, Laptop, or personal computer (PC) to power the LED-based endoscope. The connectors are Type-C USB, Android micro-USB, and computer USB.

Due to the need for optical imaging of the cervix at low-light intensities during childbirth, investigation on bioluminescence low-light intensities was carried out. Bioluminescence is a natural phenomenon of producing and emitting visible light by terrestrial organisms (such as fireflies), and marine organisms (like bacteria) [81]. The light intensity of a nonpathogenic bioluminescent bacteria (*Vibrio fischeri*) was investigated. Bioluminescence do not cause photobleaching, phototoxicity, or excitation scattering [82]. The bioluminescent bacteria (*Vibrio fischeri*) naturally generated a chemiluminescent reaction. The bacterial luciferase (a flavin-dependent monooxygenase) catalyzed the oxidation of substrates, which are reduced flavin mononucleotide ($FMNH_2$), and long-chain aliphatic (fatty) aldehyde (RCHO), by oxygen (O_2). The products of the reaction were oxidized flavin (FMN), carboxylic acid (RCOOH), and water (H_2O) with emission of blue-green light at 490nm wavelength, as shown in (1).

$$FMNH_2 + O_2 + RCHO \overset{luciferase}{\Rightarrow} FMN + H_2O + RCOOH + light(490\ nm) \quad (1)$$

Four plates of bioluminescent bacteria were donated by the Nigerian Marine Institute of Oceanography, and five plates of bioluminescent bacteria with photobacterium broth were bought from Carolina Biologicals, North Carolina USA, as shown in Fig. 8. The light intensities of the bioluminescence light were approximately within the range of 25 Lux and 55 Lux.

The LED-based endoscope was set to function at 28 Lux and 50 Lux intensities which were within the range of the bioluminescence intensities (25 Lux to 55 Lux).

The Basler ace camera with the Basler premium lens was mounted on top of the 3D printed hollow probe body. They were not inserted through the hollow probe body because of their sizes. The disposable cap and probe head had to

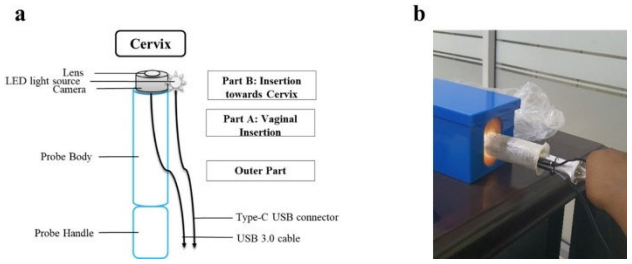

FIGURE 13. (a) Schematic diagram of insertion of the light imaging probe; (b) Insertion of the light imaging probe for image acquisition.

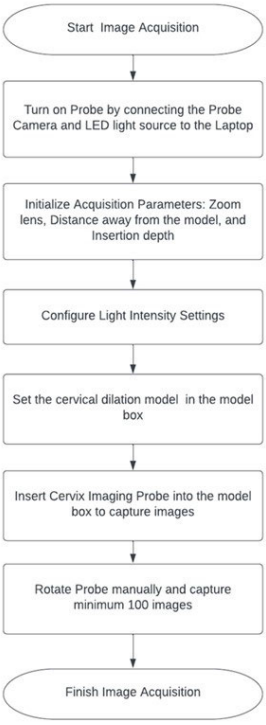

FIGURE 14. Flowchart of cervical dilation image acquisition.

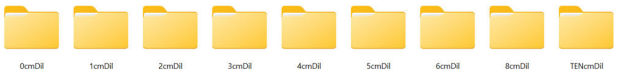

FIGURE 15. A sample of cervical dilation folders.

be removed before the camera and the lens were mounted. The white LED-based endoscope was attached by the side of the camera in its mounted position as shown in Fig. 9, then only the translucent disposable cap was placed back on the hollow probe body. Then, the light intensities of the LED-based endoscope were set to 28 Lux and 50 Lux by adjusting its knob, and using a luxmeter to measure the light intensity at different points.

B. IMAGE ACQUISITION

1) SETUP OF CERVICAL DILATION MODELS FOR IMAGE ACQUISITION

Standard Cervical Dilation simulation models, and Fetal monitoring and Labour progress model were set up for the image acquisition phase as shown in Fig. 10. They were purchased from Health Edco Childbirth graphics UK. They are majorly used by mid-wives and nursing students for realistic simulation trainings on vaginal examination, assessment of labour progress and dilation, and assessment of the

TABLE 3. Dehazing algorithm for low-light image enhancement.

ALGORITHM 1: Dehazing Algorithm for Low-Light Image Enhancement	
1.	Input: An $M \times N$ rgb image I
2.	Output: Inverted Enhanced image B
3.	#Input raw image.
4.	Imds = imageDatastore
5.	numImages = nume1 (Imds.Labels) #return the number of images
6.	For i=1 to numImages
7.	I = readimage[Imds,i] #read images from the datastore

8.	#Invert the low-light image
	AInv = Adj (I / |I|)

9.	#Apply the haze removal algorithm to the inverted low-light image
	BInv = Imreducehaze(AInv)

10.	#Invert the enhanced image
	B = Adj (BInv / |Binv|)

11.	End For

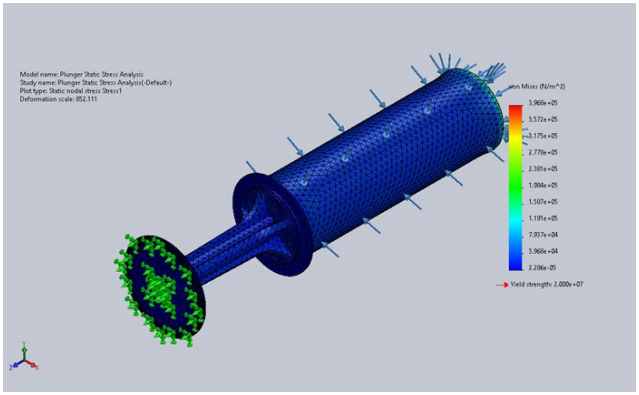

FIGURE 16. Stress distribution of static stress analysis.

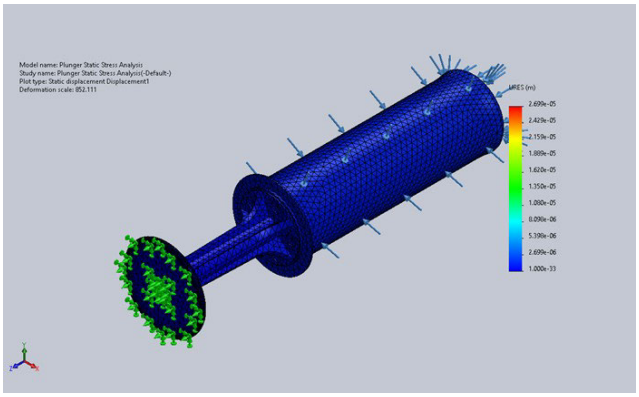

FIGURE 17. Displacement distribution of static stress analysis.

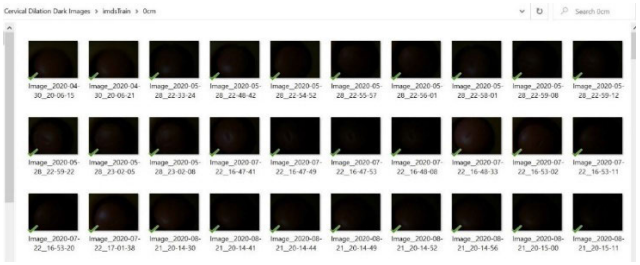

FIGURE 18. A sample of low-light cervical dilation images for 0 cm dilation.

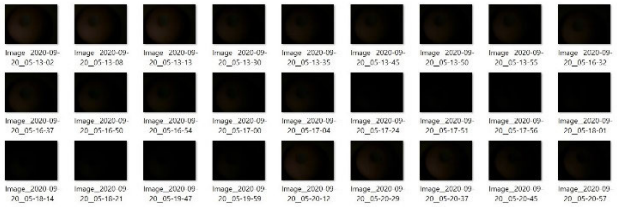

FIGURE 19. A sample of low-light cervical dilation images for 1 cm dilation.

FIGURE 20. A sample of low-light cervical dilation images for 2 cm dilation.

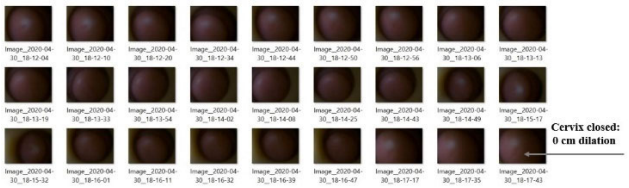

FIGURE 21. A sample of bright light cervical dilation images for 0 cm dilation.

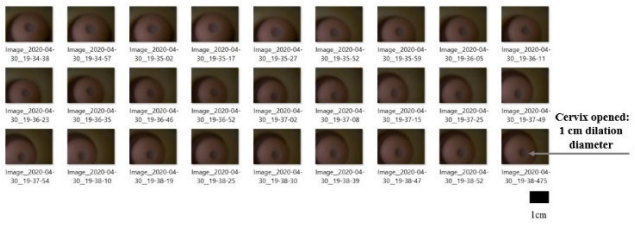

FIGURE 22. A sample of bright light cervical dilation images for 1 cm dilation.

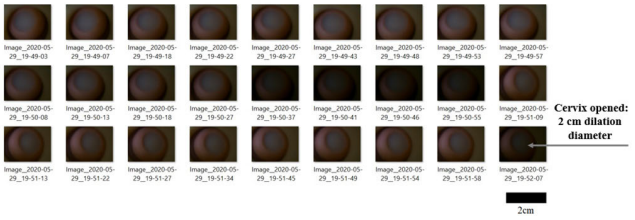

FIGURE 23. A sample of bright light cervical dilation images for 2 cm dilation.

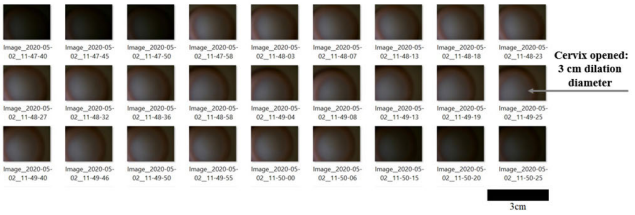

FIGURE 24. A sample of bright light cervical dilation images for 3 cm dilation.

FIGURE 25. A sample of bright light cervical dilation images for 4 cm dilation.

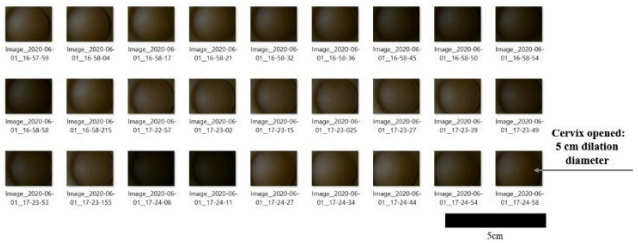

FIGURE 26. A sample of bright light cervical dilation images for 5 cm dilation.

FIGURE 27. A sample of bright light cervical dilation images for 6 cm dilation.

position of the fetal head, before performing such assessments on real patients [83]. The Fetal monitoring and Labour progress model set consists of a fetal head, vaginal wall, and model box. The cervical dilation simulation models are a set of nine individual dilation models (0 cm, 1 cm, 2 cm, 3 cm,

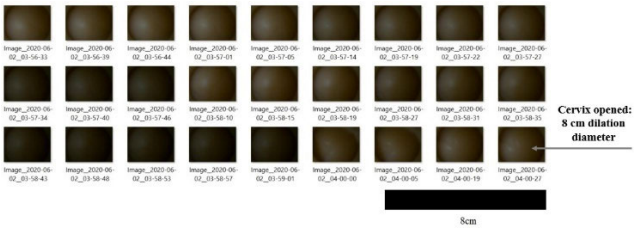

FIGURE 28. A sample of bright light cervical dilation images for 8 cm dilation.

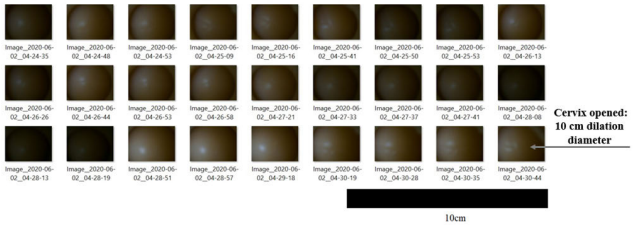

FIGURE 29. A sample of bright light cervical dilation images for 10 cm dilation.

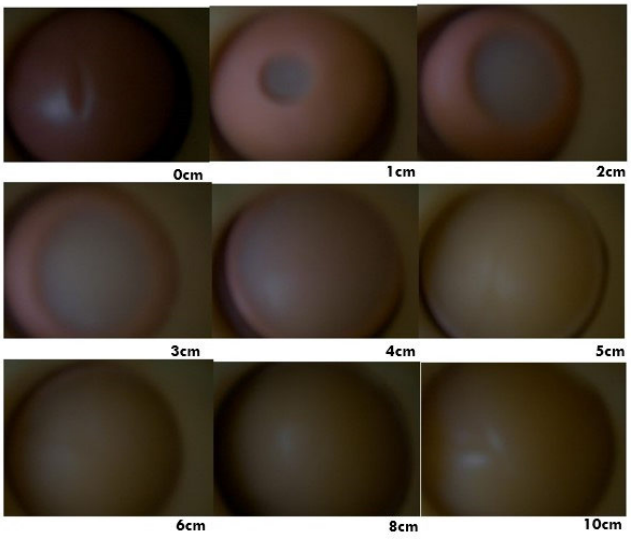

FIGURE 30. A sample of individual dilation of bright light cervical dilation images.

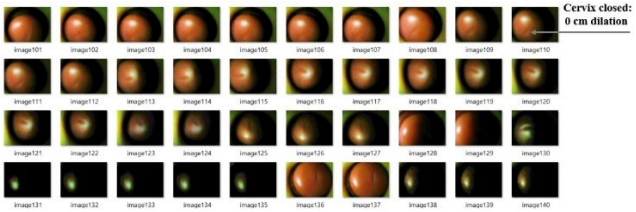

FIGURE 31. Output sample of preprocessed cervical dilation images for 0 cm dilation.

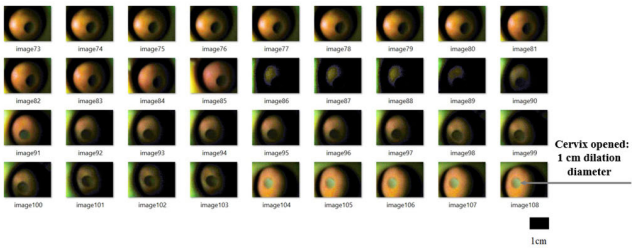

FIGURE 32. Output sample of preprocessed cervical dilation images for 1 cm dilation.

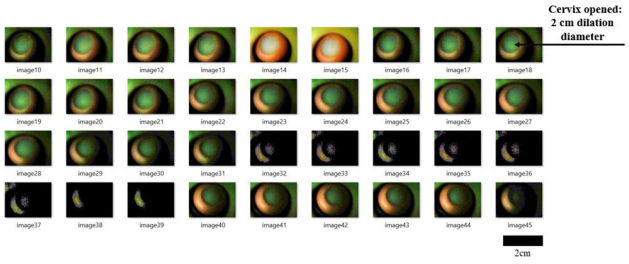

FIGURE 33. Output sample of preprocessed cervical dilation images for 2 cm dilation.

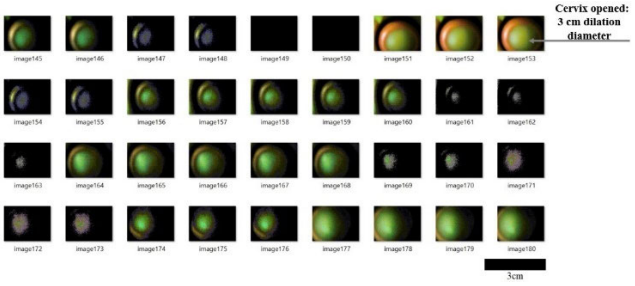

FIGURE 34. Output sample of preprocessed cervical dilation images for 3 cm dilation.

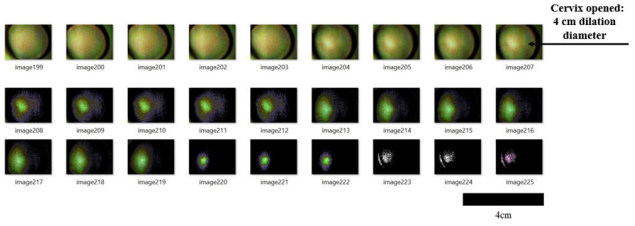

FIGURE 35. Output sample of preprocessed cervical dilation images for 4 cm dilation.

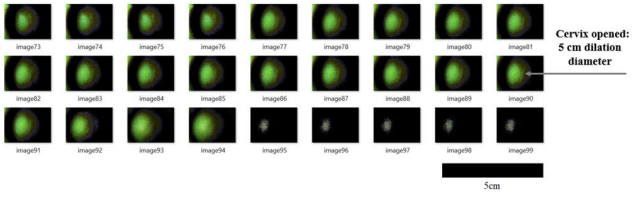

FIGURE 36. Output sample of preprocessed cervical dilation images for 5 cm dilation.

4 cm, 5 cm, 6 cm, 8 cm, and 9 cm), as labelled in Fig. 11. They are made of BIOLIKE 2 ^{TM} synthetic tissue and that is why they have a lifelike feel and greater durability. Before each use, the cervical dilation models were lightly powdered with the talcum powder provided with the models to give them

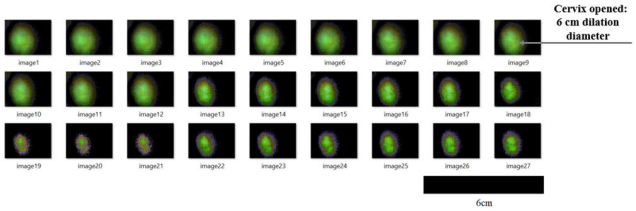

FIGURE 37. Output sample of preprocessed cervical dilation images for 6 cm dilation.

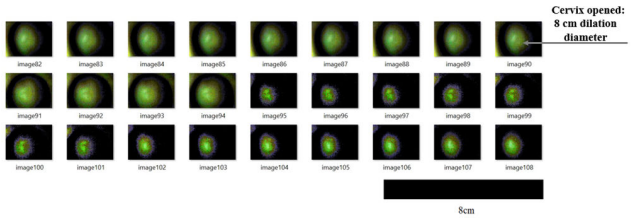

FIGURE 38. Output sample of preprocessed cervical dilation images for 8 cm dilation.

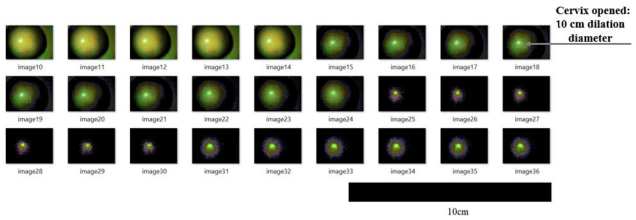

FIGURE 39. Output sample of preprocessed cervical dilation images for 10 cm dilation.

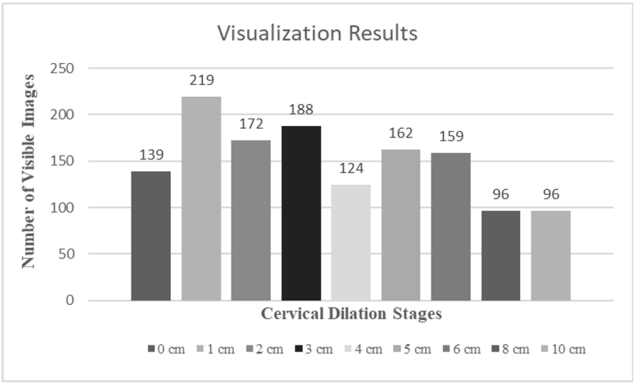

FIGURE 40. Visualization results of the preprocessed low-light cervical dilation images.

a smooth feel as instructed in the user manual. The models were treated carefully as human tissue due to the instructions given in the manual, and each of them was placed interchangeably inside the fetal monitoring and labour progress model box when it was time to capture an individual dilation model.

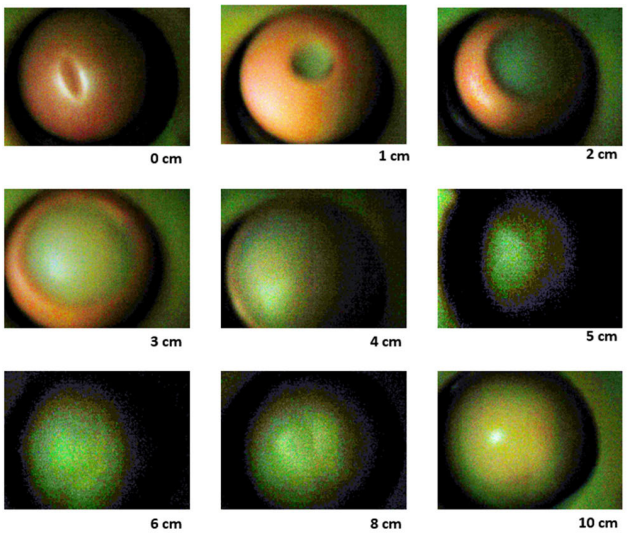

FIGURE 41. A sample of individual dilation of the preprocessed low-light cervical dilation images.

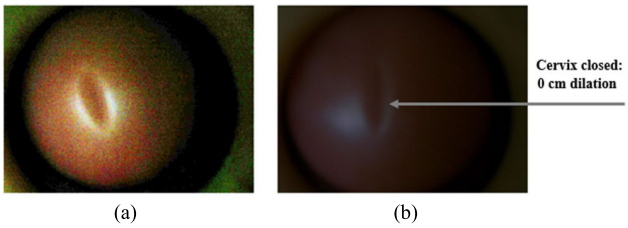

FIGURE 42. (a) A sample of 0 cm preprocessed low-light cervical dilation image (b) A sample of 0 cm bright light cervical dilation image.

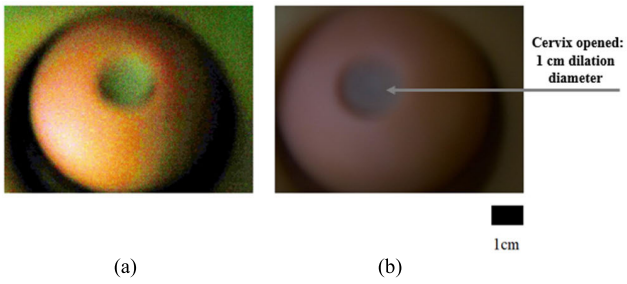

FIGURE 43. (a) A sample of 1 cm preprocessed low-light cervical dilation image (b) A sample of 1 cm bright light cervical dilation image.

2) CERVICAL DILATION IMAGE ACQUISITION SETUP

The light imaging probe was setup to acquire cervical dilation images from the simulation models. The camera of the light imaging probe was connected to an HP Spectre x360 Convertible Laptop through a USB 3.0 cable to power the camera, enable image capture, and transfer information from the camera to the laptop. The Type-C USB connector of the LED light source was plugged into the Laptop's Type-C port to power the light source. The voltage (V) from the Laptop's USB port was 5 V, while the USB 3.0 current (I) was 0.9mA. The

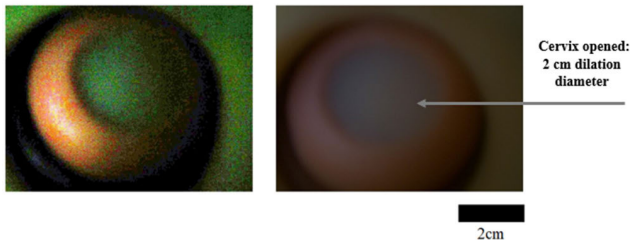

FIGURE 44. (a) A sample of 2 cm preprocessed low-light cervical dilation image (b) A sample of 2 cm bright light cervical dilation image.

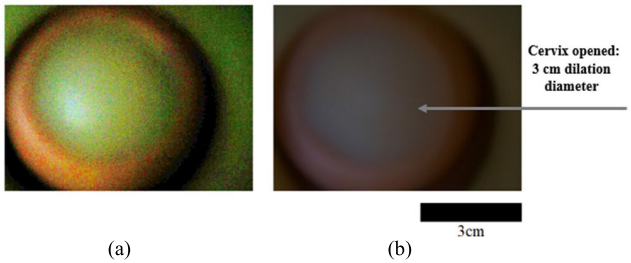

FIGURE 45. (a) A sample of 3 cm preprocessed low-light cervical dilation image (b) A sample of 3 cm bright light cervical dilation image.

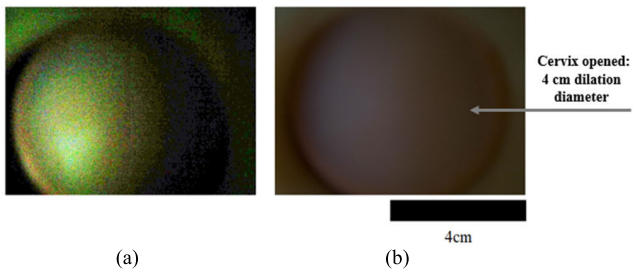

FIGURE 46. (a) A sample of 4 cm preprocessed low-light cervical dilation image (b) A sample of 4 cm bright light cervical dilation image.

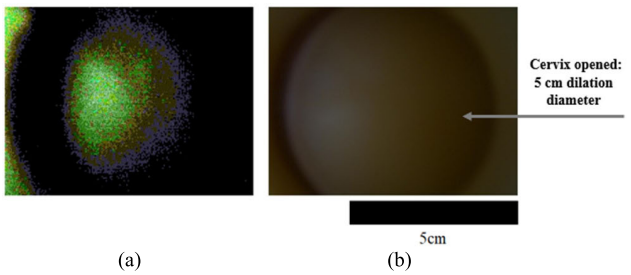

FIGURE 47. (a) A sample of 5 cm preprocessed low-light cervical dilation image (b) A sample of 5 cm bright light cervical dilation image.

schematic diagram of the probe setup with a photographed setup is shown in Fig. 12. The Laptop specifications are Intel Core i7 Processor, CPU at 1.80 Ghz and 8 GB RAM. Basler Pylon Viewer software was installed and opened on the laptop for image acquisition and visualization.

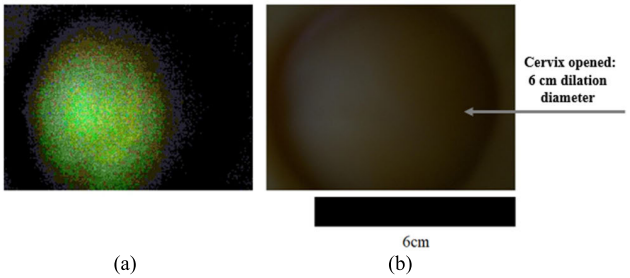

FIGURE 48. (a) A sample of 6 cm preprocessed low-light cervical dilation image (b) A sample of 6 cm bright light cervical dilation image.

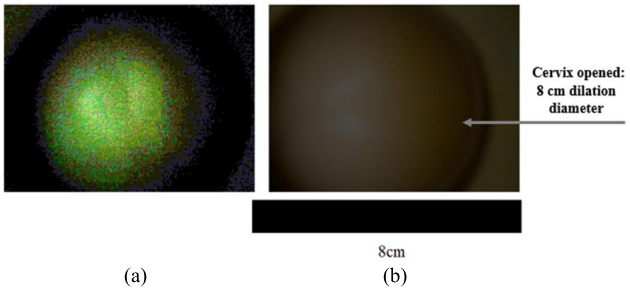

FIGURE 49. (a) A sample of 8 cm preprocessed low-light cervical dilation image (b) A sample of 8 cm bright light cervical dilation image.

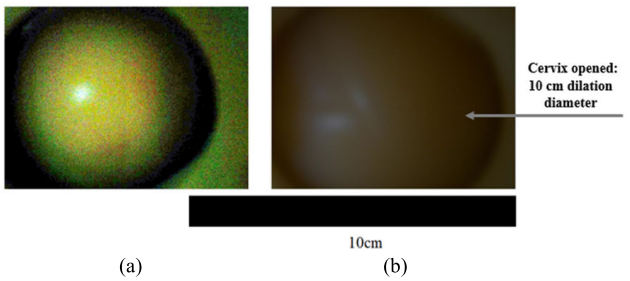

FIGURE 50. (a) A sample of 10 cm preprocessed low-light cervical dilation image (b) A sample of 10 cm bright light cervical dilation image.

3) CERVICAL DILATION IMAGE ACQUISITION PROTOCOL

The light imaging probe was inserted into the model box that contained the vaginal wall and an individual cervical dilation model (per time), for image capturing, as shown in Fig. 13. Fig. 14 illustrates the flowchart of the cervical dilation image acquisition.

The following steps are the image acquisition protocol:

- Probe camera was set to 3 calibrated zooms (0mm, 1.18mm, 4mm);
- Probe was inserted at 2 insertion depths (2cm and 3cm);
- LED light intensities were set at low-light intensities (28 Lux and 50 Lux);
- Images were acquired as probe was rotated manually.

The acquired image data set were stored, arranged, and labelled in nine dilation folders on the Laptop. The low-light images acquired were stored in a low-light image datastore,

and each dilation folder had 320 images. The datastore had a total of 2,880 images since there were nine dilation folders for each dilation model. Fig. 15 shows a sample of the dilation folders.

Furthermore, the light imaging probe was used to acquire cervical dilation images under bright light, for comparisons with the images acquired under low-light. The LED-based endoscope of the probe was set at bright light intensities of 650 Lux, 930 Lux and 1852 Lux.

4) IMAGE PREPROCESSING

Image enhancement plays a very significant role in image processing and computer vision [84]. It is one of the most common phases in image preprocessing [74]. It is the process of adjusting images to give a more suitable and enhanced quality image [85], [86]. A low-light image enhancement algorithm was used to preprocess (improve the visibility of) the acquired low-light cervical dilation images. The algorithm is a dehazing algorithm known as image reduce (imreduce) haze removal algorithm as shown in Table. 3. The Integrated Development Environment (IDE) that was implemented for the image preprocessing was MATLAB® R2020b Image Processing Toolbox.

The haze removal algorithm comprises of three preprocessing steps [84]:

- Step 1: Invert low-light image.
- Step 2: Apply image reduce haze removal algorithm to the inverted low-light image.
- Step 3: Invert the enhanced image.

All enhanced images were stored in a low-light enhanced image datastore where each dilation folder had 320 enhanced low-light images, making a total of 2,880 images due to the nine dilation folders.

V. RESULTS

This section comprises of the finite element analysis results of the light imaging probe, and the results of the image acquisition phase and image preprocessing phase.

A. FINITE ELEMENT ANALYSIS RESULTS OF THE LIGHT IMAGING PROBE

The results of the static stress Finite Element Analysis show the stress distribution with von Mises stress, and the displacement in Fig. 16 and Fig. 17 respectively. The blue color region in Fig. 16 represents the lower von Mises values, and the higher von Mises values is the red region. The value of the maximum von Mises stress result obtained was 3.968 MPa, and the yield strength is 2.000. In Fig. 17, the value of the maximum displacement result obtained was 2.699. The blue color region represents the lower displacement values, and the higher displacement values is the red region.

B. IMAGE ACQUISITION RESULTS

Samples of 0 cm, 1 cm, and 2 cm cervical dilation images that were acquired by the light imaging probe under low-light intensities (28 Lux and 50 Lux) are shown in Fig. 18, Fig. 19 and Fig. 20 respectively.

Samples of 0 cm, 1 cm, 2 cm, 3 cm, 4 cm, 5 cm, 6 cm, 8 cm and 10 cm cervical dilation images that were acquired by the light imaging probe under bright light intensities (650 Lux, 930 Lux and 1852 Lux) are shown in Fig. 21, Fig. 22, Fig. 23, Fig. 24, Fig. 25, Fig. 26, Fig. 27, Fig. 28 and Fig. 29 respectively. A sample of individual dilation of the bright light cervical dilation images is shown in Fig. 30

C. IMAGE PREPROCESSING RESULTS

The hazing removal algorithm that was applied on the acquired low-light cervical dilation images (raw images) gave an output of preprocessed images. The samples of preprocessed 0 cm, 1 cm, 2 cm, 3 cm, 4 cm, 5 cm, 6 cm, 8 cm and 10 cm cervical dilation images are shown in Fig. 31, Fig. 32, Fig. 33, Fig. 34, Fig. 35, Fig. 36, Fig. 37, Fig. 38, and Fig. 39 respectively.

There were 139 visible images out of 320 preprocessed low-light cervical dilation images for the 0 cm dilation; 219 visible images out of 320 images for the 1 cm dilation; 172 visible images out of 320 images for the 2 cm dilation; 188 visible images out of 320 images for the 3 cm dilation; 124 visible images out of 320 images for the 4 cm dilation; 162 visible images out of 320 images for the 5 cm dilation; 159 visible images out of 320 images for the 6 cm dilation; 96 visible images out of 320 images for the 8 cm dilation; and 96 visible images out of 320 images for the 10 cm dilation. Hence, the preprocessed images showed 47% visualization. Fig. 40 shows the visualization results of the preprocessed low-light cervical dilation images.

A sample of individual dilation of the preprocessed low-light images is shown in Fig. 41. Combined samples of preprocessed low-light images and bright light images for 0 cm, 1 cm, 2 cm, 3 cm, 4 cm, 5 cm, 6 cm, 8 cm and 10 cm dilations are shown in Fig. 42, Fig. 43, Fig. 44, Fig. 45, Fig. 46, Fig. 47, Fig. 48, Fig. 49 and Fig. 50 respectively, for comparisons.

VI. DISCUSSION

This research has demonstrated the use of optical imaging in acquiring images of cervical dilation simulation models. The prototype of the low-intensity light imaging probe was developed for image acquisition, and the acquired images were preprocessed. The results obtained showed that cervical dilation images captured in low-light can be enhanced. The images in Fig. 42, Fig. 43, Fig. 44, Fig. 45, Fig. 46, Fig. 47, Fig. 48, Fig. 49 and Fig. 50 showed that the preprocessed low-light images were similar to the bright light images. They were also similar to the standard cervical dilation models in Fig. 11.

Studies have shown that vaginal examination method for cervical dilation assessment is highly subjective due to the finger size and experience of the obstetricians and midwives [11], [19], [20], [31]. However, this research has demonstrated that a low-light imaging probe can be inserted into the

vagina to acquire cervical dilation images instead of inserting fingers into the vagina to feel the cervix, mentally visualize it, and assess cervical dilation using the vaginal examination method. Studies have been reported that some women viewed the insertion of fingers as embarrassing, emotionally traumatic, and privacy-invasive especially in prolonged labour where different medical personnel have to carry out the assessment [9], [25], [26], [29].

In this research, the light imaging probe captured images of a fully dilated cervix at a distance of 2 cm and 3 cm from the cervix, in contrast to some of the electronic systems that had the limitations of placing the sensors on the cervix to assess cervical dilation when it was almost fully dilated [27], [33].

Fig. 40 showed that 1 cm dilation had the most visible preprocessed low-light images, followed by 3 cm, 2 cm, 5 cm, 6 cm, 0 cm, 4 cm, and 8 cm and 10 cm dilations respectively. The visualization percentage of the preprocessed low-light images was 47%. Further work would be carried out on the light imaging probe. A higher resolution camera, with a low-light intensity of 50 lux will be used. Also, the probe will be miniaturized to a diameter of about 3 mm for easy and comfortable insertion. An improved prototype that is biocompatible would be developed to carry out clinical studies. Further research on machine learning and deep learning classification tasks would be explored on the images for automated cervical dilation assessment.

ACKNOWLEDGMENT

The authors thank God for divine wisdom.

REFERENCES

[1] D. T. Lavender, "Improving quality of care during labour and childbirth and in the immediate postnatal period," *Best Pract. Res. Clin. Obstetrics Gynaecol.*, vol. 36, pp. 57–67, Oct. 2016, doi: 10.1016/j.bpobgyn.2016.05.011.

[2] Ö. Tunçalp, W. Were, C. MacLennan, O. Oladapo, A. Gülmezoglu, R. Bahl, B. Daelmans, M. Mathai, L. Say, F. Kristensen, M. Temmerman, and F. Bustreo, "Quality of care for pregnant women and newborns—The WHO vision," *BJOG, Int. J. Obstetrics Gynaecol.*, vol. 122, no. 8, pp. 1045–1049, Jul. 2015, doi: 10.1111/1471-0528.13451.

[3] *WHO Labour Care Guide: User's Manual*, WHO, Geneva, Switzerland 2020.

[4] N. F. Moran, M. Naidoo, and J. Moodley, "Reducing maternal mortality on a countrywide scale: The role of emergency obstetric training," *Best Pract. Res. Clin. Obstetrics Gynaecol.*, vol. 29, no. 8, pp. 1102–1118, Nov. 2015, doi: 10.1016/j.bpobgyn.2015.08.002.

[5] A. Nove et al., "Potential impact of midwives in preventing and reducing maternal and neonatal mortality and stillbirths: A lives saved tool modelling study," *Lancet Global Health*, vol. 9, no. 1, pp. e24–e32, Jan. 2021, doi: 10.1016/S2214-109X(20)30397-1.

[6] K. Lunze, A. Higgins-Steele, A. Simen-Kapeu, L. Vesel, J. Kim, and K. Dickson, "Innovative approaches for improving maternal and newborn health—A landscape analysis," *BMC Pregnancy Childbirth*, vol. 15, no. 1, p. 337, Dec. 2015, doi: 10.1186/s12884-015-0784-9.

[7] O. Olonade, T. I. Olawande, O. J. Alabi, and D. Imhonopi, "Maternal mortality and maternal health care in Nigeria: Implications for socio-economic development," *Open Access Macedonian J. Med. Sci.*, vol. 7, no. 5, pp. 849–855, Mar. 2019.

[8] A. O. Adejumo, E. A. Suleiman, H. I. Okagbue, P. E. Oguntunde, and O. A. Odetunmibi, "Quantitative evaluation of pregnant women delivery status' records in Akure, Nigeria," *Data Brief*, vol. 16, pp. 127–134, Feb. 2018, doi: 10.1016/j.dib.2017.11.041.

[9] S. Downe, G. M. Gyte, H. Dahlen, and M. Singata, "Routine vaginal examinations for assessing progress of Labour to improve outcomes for women and babies at term," *Cochrane Database Systematic Rev.*, vol. 7, Jul. 2013, Art. no. CD010088.

[10] M. S. Balikuddembe, N. M. Tumwesigye, P. K. Wakholi, and T. Tylleskär, "Computerized childbirth monitoring tools for health care providers managing labor: A scoping review," *JMIR Med. Informat.*, vol. 5, no. 2, Jun. 2017, Art. no. e6959.

[11] G. Moncrieff, G. M. Gyte, H. G. Dahlen, G. Thomson, M. Singata-Madliki, A. Clegg, and S. Downe, "Routine vaginal examinations compared to other methods for assessing progress of labour to improve outcomes for women and babies at term," *Cochrane Database Systematic Rev.*, vol. 2022, no. 3, Mar. 2022, Art. no. CD010088, doi: 10.1002/14651858.CD010088.pub3.

[12] H. Feltovich and L. Carlson, "New techniques in evaluation of the cervix," in *Seminars Perinatology*, vol. 41, no. 8. Amsterdam, The Netherlands: Elsevier, 2017, pp. 477–484.

[13] *Intrapartum Care for a Positive Childbirth Experience*, World Health Organization, WHO, Geneva, Switzerland, 2018, p. 150.

[14] J. Nizard, S. Haberman, Y. Paltieli, R. Gonen, G. Ohel, D. Nicholson, and Y. Ville, "How reliable is the determination of cervical dilation? Comparison of vaginal examination with spatial position-tracking ruler," *Amer. J. Obstetrics Gynecol.*, vol. 200, no. 4, pp. 402.e1–402.e4, Apr. 2009, doi: 10.1016/j.ajog.2009.01.002.

[15] S. Casciaro, F. Conversano, E. Casciaro, G. Soloperto, M. Stark, and A. Perrone, "Quantitative and automatic echographic monitoring of labor progression," in *Proc. IEEE Int. Ultrason. Symp.*, Oct. 2012, pp. 1–4, doi: 10.1109/ULTSYM.2012.0660.

[16] J.-K. Hoh, K.-J. Cha, M.-I. Park, M.-L. Ting Lee, and Y.-S. Park, "Estimating time to full uterine cervical dilation using genetic algorithm," *Kaohsiung J. Med. Sci.*, vol. 28, no. 8, pp. 423–428, Aug. 2012, doi: 10.1016/j.kjms.2012.02.012.

[17] A. Shepherd and H. Cheyne, "The frequency and reasons for vaginal examinations in labour," *Women Birth*, vol. 26, no. 1, pp. 49–54, Mar. 2013, doi: 10.1016/j.wombi.2012.02.001.

[18] E. Buchmann and E. Libhaber, "Accuracy of cervical assessment in the active phase of labour," *BJOG, Int. J. Obstetrics Gynaecol.*, vol. 114, no. 7, pp. 833–837, 2007, doi: 10.1111/j.1471-0528.2007.01386.x.

[19] M. Brancadoro, S. Tognarelli, F. Fambrini, A. Ragusa, and A. Menciassi, "Devices for measuring cervical dilation during labor: Systematic review and meta-analysis," *Obstetrical Gynecolog. Surv.*, vol. 73, no. 4, pp. 231–241, 2018.

[20] E. L. Martin, B. Firman, and V. Berghella, "Novel device vs manual examinations for the measurement of cervical dilation in labor: A randomized controlled trial," *Amer. J. Obstetrics Gynecol. MFM*, vol. 3, no. 3, May 2021, Art. no. 100328, doi: 10.1016/j.ajogmf.2021.100328.

[21] J. M. G. Crane and D. Hutchens, "Transvaginal ultrasonographic measurement of cervical length in asymptomatic high-risk women with a short cervical length in the previous pregnancy," *Ultrasound Obstetrics Gynecol.*, vol. 38, no. 1, pp. 38–43, Jul. 2011, doi: 10.1002/uog.9004.

[22] O. Reichman and A. Samueloff, "The use of cervical sonography to differentiate true from false labor in term patients presenting for labor check," *Amer. J. Obstetrics Gynecol.*, vol. 215, no. 6, pp. 811–812, Dec. 2016, doi: 10.1016/j.ajog.2016.07.026.

[23] J. P. Nott, E. A. Bonney, J. D. Pickering, and N. A. B. Simpson, "The structure and function of the cervix during pregnancy," *Transl. Res. Anatomy*, vol. 2, pp. 1–7, Mar. 2016, doi: 10.1016/j.tria.2016.02.001.

[24] W. A. Hassan, *Fetal and Maternal Imaging: Ultrasound Assessment of Labor Parameters*. Giles Ln, Canterbury: University of Kent, 2018.

[25] G. Teskereci, H. Yangın, and A. Akpınar, "Experiences of women regarding vaginal examination during labor: A qualitative study," *Health Care Women Int.*, vol. 41, no. 1, pp. 75–88, Jan. 2020, doi: 10.1080/07399332.2019.1590361.

[26] K. Adu-Bonsaffoh, H. Mehrtash, C. Guure, E. Maya, J. P. Vogel, T. A. Irinyenikan, A. K. Aderoba, M. D. Balde, R. Adanu, M. A. Bohren, and Ö. Tuncalp, "Vaginal examinations and mistreatment of women during facility-based childbirth in health facilities: Secondary analysis of labour observations in Ghana, Guinea and Nigeria," *BMJ Global Health*, vol. 5, no. 2, Nov. 2021, Art. no. e006640, doi: 10.1136/bmjgh-2021-006640.

[27] Z. Boyd, R. DiGrazia, A. Fanselow, R. Griffin, and E. Lezama, "Detection and notification of preterm labor in high-risk pregnancies," in *Proc. IEEE Great Lakes Biomed. Conf. (GLBC)*, Apr. 2017, p. 1, doi: 10.1109/GLBC.2017.7928900.

[28] P. Verma, A. K. Ghosh, R. C. Huck, S. Cheng, S. Chen, M. Martens, and A. Kaul, "Continuous wireless monitoring of the cervical dilation of a pregnant woman," in *Proc. IEEE Int. Workshop Med. Meas. Appl.*, May 2008, pp. 93–96.

[29] G. Güneş and Z. Karaçam, "The feeling of discomfort during vaginal examination, history of abuse and sexual abuse and post-traumatic stress disorder in women," *J. Clin. Nursing*, vol. 26, nos. 15–16, pp. 2362–2371, Aug. 2017, doi: 10.1111/jocn.13574.

[30] H. Feltovich, "Cervical evaluation: From ancient medicine to precision medicine," *Obstetrics Gynecol.*, vol. 130, no. 1, pp. 51–63, 2017.

[31] W. A. Hassan, S. Taylor, and C. Lees, "Intrapartum ultrasound for assessment of cervical dilatation," *Amer. J. Obstetrics Gynecol. MFM*, vol. 3, no. 6, Nov. 2021, Art. no. 100448, doi: 10.1016/j.ajogmf.2021.100448.

[32] D. Dubey and T. Baird, "Cervical dilation measurement apparatus," U.S. Patents 20 070 255 185 A1, Oct. 12, 2010.

[33] P. Verma, "Designing a wireless sensor system for continuous monitoring of the cervical dilation of a pregnant woman," *Int. J. Adv. Media Commun.*, vol. 3, nos. 1–2, pp. 126–138, 2009.

[34] S. Usman and C. Lees, "Benefits and pitfalls of the use of intrapartum ultrasound," *Australas. J. Ultrasound Med.*, vol. 18, no. 2, pp. 53–59, May 2015, doi: 10.1002/j.2205-0140.2015.tb00042.x.

[35] O. Gluck, Y. Mizrachi, H. Ganer Herman, J. Bar, M. Kovo, and E. Weiner, "The correlation between the number of vaginal examinations during active labor and febrile morbidity, a retrospective cohort study," *BMC Pregnancy Childbirth*, vol. 20, no. 1, p. 246, Dec. 2020, doi: 10.1186/s12884-020-02925-9.

[36] L. Say, "Global causes of maternal death: A WHO systematic analysis," *Lancet Global Health*, vol. 2, no. 6, pp. e323–e333, 2014, doi: 10.1016/S2214-109X(14)70227-X.

[37] *Managing Complications in Pregnancy and Childbirth: A Guide for Midwives and Doctors*, WHO, World Health Organization, Geneva, Switzerland, 2017.

[38] *WHO Safe Childbirth Checklist Implementation Guide: Improving the Quality of Facility-Based Delivery for Mothers and Newborns*, WHO, Geneva, Switzerland 2015.

[39] Z. Mohaghegh, S. Jahanfar, P. Abedi, and M. A. A. El Aziz, "Reliability of ultrasound versus digital vaginal examination in detecting cervical dilatation during labor: A diagnostic test accuracy systematic review," *Ultrasound J.*, vol. 13, no. 1, p. 37, Dec. 2021, doi: 10.1186/s13089-021-00239-1.

[40] S. Usman, H. Barton, C. Wilhelm-Benartzi, and C. C. Lees, "Ultrasound is better tolerated than vaginal examination in and before labour," *Austral. New Zealand J. Obstetrics Gynaecol.*, vol. 59, no. 3, pp. 362–366, Jun. 2019, doi: 10.1111/ajo.12864.

[41] J. Kim, S. Kim, S. Jeon, and S. Jung, "A longitudinal study investigating cervical changes during labor using a wireless ultrasound device," *J. Maternal-Fetal Neonatal Med.*, vol. 31, no. 13, pp. 1787–1791, Jul. 2018, doi: 10.1080/14767058.2017.1329292.

[42] Y. Sharf, D. Farine, M. Batzalel, Y. Megel, M. Shenhav, A. Jaffa, and O. Barnea, "Continuous monitoring of cervical dilatation and fetal head station during labor," *Med. Eng. Phys.*, vol. 29, no. 1, pp. 61–71, Jan. 2007, doi: 10.1016/j.medengphy.2006.01.005.

[43] Y. A. Wiafe, B. Whitehead, H. Venables, E. T. Dassah, and T. M. Eggebø, "Intrapartum ultrasound assessment of cervical dilatation and its value in detecting active labor," *J. Ultrasound*, vol. 21, no. 3, pp. 233–239, Sep. 2018, doi: 10.1007/s40477-018-0309-2.

[44] T. O. Takpor and A. A. Atayero, "Advances in current techniques for monitoring the progress of child delivery," in *Proceedings of the World Congress on Engineering and Computer Science*, vol. 2. Hong Kong: Newswood Limited, 2014, pp. 781–784. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84918542101&partnerID=40&md5=05def09f6ebf6d9e97736f9021b8024c

[45] T. Van Dessel, J. H. Frijns, F. T. Kok, and H. C. Wallenburg, "Assessment of cervical dilatation during labor: A review," *Eur. J. Obstetrics Gynecol. Reproductive Biol.*, vol. 41, no. 3, pp. 71–165, Oct. 1991.

[46] F. Conversano, M. Peccarisi, P. Pisani, M. D. Paola, T. D. Marco, R. Franchini, A. Greco, and S. Casciaro, "Automatic ultrasound technique to measure angle of progression during labor," *Ultrasound Obstetrics Gynecology, Wiley*, vol. 50, no. 6, pp. 766–775, 2017, doi: 10.1002/uog.17441.

[47] C. Kaur and U. Garg, "Artificial intelligence techniques for cancer detection in medical image processing: A review," *Mater. Today, Proc.*, vol. 81, pp. 806–809, May 2023, doi: 10.1016/j.matpr.2021.04.241.

[48] C. Balas, "Review of biomedical optical imaging—A powerful, non-invasive, non-ionizing technology for improving in vivo diagnosis," *Meas. Sci. Technol.*, vol. 20, no. 10, Oct. 2009, Art. no. 104020.

[49] H. Kim and J. H. Chang, "Increased light penetration due to ultrasound-induced air bubbles in optical scattering media," *Sci. Rep.*, vol. 7, no. 1, Nov. 2017, Art. no. 16105.

[50] *National Institute of Biomedical Imaging and Bioengineering. Optical Imaging*. Accessed: Jan. 10, 2019. [Online]. Available: https://www.nibib.nih.gov/science-education/science-topics/optical-imaging

[51] A. P. Dhawan, B. D'Alessandro, and X. Fu, "Optical imaging modalities for biomedical applications," *IEEE Rev. Biomed. Eng.*, vol. 3, pp. 69–92, 2010, doi: 10.1109/RBME.2010.2081975.

[52] P. Aslan, R. L. Kuo, K. Hazel, R. K. Babayan, and G. M. Preminger, "Advances in digital imaging during endoscopic surgery," *J. Endourol.*, vol. 13, no. 4, pp. 251–255, May 1999, doi: 10.1089/end.1999.13.251.

[53] P. Sowa, J. Rutkowska-Talipska, K. Rutkowski, B. Kosztyła-Hojna, and R. Rutkowski, "Optical radiation in modern medicine," *Adv. Dermatol. Allergol.*, vol. 4, pp. 246–251, Aug. 2013.

[54] S. G. Kola and S. Masilamani, "Isolation and characterization of bioluminescent bacteria from marine organisms," *Indian J. Geo Marine Sci., Nat. Inst. Sci. Commun. Policy Res., India*, vol. 46, no. 4, pp. 797–801, Apr. 2017.

[55] F. Vallet, B. Tyl, O. Pialot, and D. Millet, "Is this system ECO-innovative? A case-based workshop," in *Proc. 21st Int. Conf. Eng. Design (ICED)*, Vancouver, BC, Canada, Aug. 2017, pp. 1–10. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01527681

[56] S. Uchida, "Image processing and recognition for biological images," *Develop., Growth Differentiation*, vol. 55, no. 4, pp. 523–549, May 2013, doi: 10.1111/dgd.12054.

[57] S. Mohapatra, T. Swarnkar, and J. Das, "Deep convolutional neural network in medical image processing," in *Handbook of Deep Learning in Biomedical Engineering*, V. E. Balas, B. K. Mishra, and R. Kumar Eds. New York, NY, USA: Academic, 2021, pp. 25–60.

[58] B. L. Craine, E. R. Craine, C. J. O'Toole, and Q. Ji, "Digital imaging colposcopy: Corrected area measurements using shape-from-shading," *IEEE Trans. Med. Imag.*, vol. 17, no. 6, pp. 1003–1010, Dec. 1998, doi: 10.1109/42.746633.

[59] V. Chandran, M. G. Sumithra, A. Karthick, T. George, M. Deivakani, B. Elakkiya, U. Subramaniam, and S. Manoharan, "Diagnosis of cervical cancer based on ensemble deep learning network using colposcopy images," *BioMed Res. Int.*, vol. 2021, pp. 1–15, May 2021, doi: 10.1155/2021/5584004.

[60] Z. He, P. Wang, Y. Liang, Z. Fu, and X. Ye, "Clinically available optical imaging technologies in endoscopic lesion detection: Current status and future perspective," *J. Healthcare Eng.*, vol. 2021, Feb. 2021, Art. no. 7594513, doi: 10.1155/2021/7594513.

[61] C. T. Lam, M. S. Krieger, J. E. Gallagher, B. Asma, L. C. Muasher, J. W. Schmitt, and N. Ramanujam, "Design of a novel low cost point of care tampon (POCkeT) colposcope for use in resource limited settings," *PLoS ONE*, vol. 10, no. 9, Sep. 2015, Art. no. e0135869, doi: 10.1371/journal.pone.0135869.

[62] B. C. Felipe, R. V. Carlos, and G. Olarte, "Elimination of brightness and reconstruction of cervix images for diagnosis in cervical cancer," in *Proc. Congreso Argentino de Ciencias de la Informática y Desarrollos de Investigación (CACIDI)*, Nov. 2018, pp. 1–5, doi: 10.1109/CACIDI.2018.8584354.

[63] C. T. Lam, "The pocket colposcope, a novel low cost digital colposcope, to improve access to cervical screening in resource limited settings," Ph.d. dissertation, Duke Univ., 2019, Accessed: Oct. 8, 2021. [Online]. Available: https://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/18265/Lam_duke_0066D_14904.pdf

[64] C. T. Lam, J. Mueller, B. Asma, M. Asiedu, M. S. Krieger, R. Chitalia, D. Dahl, P. Taylor, J. W. Schmitt, and N. Ramanujam, "An integrated strategy for improving contrast, durability, and portability of a pocket colposcope for cervical cancer screening and diagnosis," *PLoS ONE*, vol. 13, no. 2, Feb. 2018, Art. no. e0192530, doi: 10.1371/journal.pone.0192530.

[65] K. Fernandes, J. S. Cardoso, and J. Fernandes, "Automated methods for the decision support of cervical cancer screening using digital colposcopies," *IEEE Access*, vol. 6, pp. 33910–33927, 2018, doi: 10.1109/ACCESS.2018.2839338.

[66] J. L. Mueller, E. Asma, C. T. Lam, M. S. Krieger, J. E. Gallagher, A. Erkanli, R. Hariprasad, J. S. Malliga, L. C. Muasher, B. Mchome, O. Oneko, P. Taylor, G. Venegas, A. Wanyoro, R. Mehrotra, J. W. Schmitt, and N. Ramanujam, "International image concordance study to compare a point-of-care tampon colposcope with a standard-of-care colposcope," *J. Lower Genital Tract Disease*, vol. 21, no. 2, pp. 112–119, 2017.

[67] N. Ramanujam and B. Crouch, "Democratizing cancer diagnostics and therapeutics through precision medicine," *Technol. Innov.*, vol. 20, no. 4, pp. 399–413, Aug. 2019.
[68] M. N. Asiedu, J. Agudogo, M. S. Krieger, R. Miros, R. J. Proeschold-Bell, J. W. Schmitt, and N. Ramanujam, "Design and preliminary analysis of a vaginal inserter for speculum-free cervical cancer screening," *PLoS ONE*, vol. 12, no. 5, May 2017, Art. no. e0177782.
[69] M. N. Asiedu, J. S. Agudogo, M. E. Dotson, E. Skerrett, M. S. Krieger, C. T. Lam, D. Agyei, J. Amewu, K. Asah-Opoku, M. Huchko, J. W. Schmitt, A. Samba, E. Srofenyoh, and N. Ramanujam, "A novel speculum-free imaging strategy for visualization of the internal female lower reproductive system," *Sci. Rep.*, vol. 10, no. 1, Oct. 2020, Art. no. 16570, doi: 10.1038/s41598-020-72219-9.
[70] X. Hong, V. K. Nagarajan, D. H. Mugler, and B. Yu, "Smartphone microendoscopy for high resolution fluorescence imaging," *J. Innov. Opt. Health Sci.*, vol. 9, no. 5, Sep. 2016, Art. no. 1650046.
[71] C. Wang, "Dual modal fluorescent colposcope combined with near-infrared fluorescent dye TMTP1-PEG4-ICG to detect cervical lesions," *Biomed. Opt. Exp.*, vol. 11, no. 12, pp. 7120–7131, 2020.
[72] S. Sharma, S. Malik, and P. Jain, "A detailed study of digital image processing," *IIOAB J.*, vol. 9, no. 2, pp. 33–42, 2018.
[73] V. K. Mishra, S. Kumar, and N. Shukla, "Image acquisition and techniques to perform image acquisition," *SAMRIDDHI, J. Phys. Sci., Eng. Technol.*, vol. 9, no. 1, pp. 21–24, Jun. 2017.
[74] R. D. Putra, T. W. Purboyo, and L. Prasasti, "A review of image enhancement methods," *Int. J. Appl. Eng. Res.*, vol. 12, no. 23, pp. 13596–13603, 2017.
[75] S. D. Shelare, K. R. Aglawe, and P. B. Khope, "Computer aided modeling and finite element analysis of 3-D printed drone," *Mater. Today, Proc.*, vol. 47, pp. 3375–3379, Jan. 2021.
[76] S. Bhagia, K. Bornani, R. Agrawal, A. Satlewal, J. Ďurkovič, R. Lagaňa, M. Bhagia, C. G. Yoo, X. Zhao, V. Kunc, Y. Pu, S. Ozcan, and A. J. Ragauskas, "Critical review of FDM 3D printing of PLA biocomposites filled with biomass resources, characterization, biodegradability, upcycling and opportunities for biorefineries," *Appl. Mater. Today*, vol. 24, Sep. 2021, Art. no. 101078, doi: 10.1016/j.apmt.2021.101078.
[77] N.-A. A. B. Taib, "A review on poly lactic acid (PLA) as a biodegradable polymer," *Polym. Bull.*, vol. 80, no. 2, pp. 1179–1213, 2022.
[78] M. Ghasemieshkaftaki, M. A. Ortiz, and P. M. Bluyssen, "An overview of transparent and translucent 3D-printed façade prototypes and technologies," in *Proc. Healthy Buildings Eur. Online Conf.*, 2021, pp. 83–91.
[79] E. D. Marchi, S. Pigliafreddo, A. Banterle, M. Parolini, and A. Cavaliere, "Plastic packaging goes sustainable: An analysis of consumer preferences for plastic water bottles," *Environ. Sci. Policy*, vol. 114, pp. 305–311, Dec. 2020, doi: 10.1016/j.envsci.2020.08.014.
[80] A. G. Basler and A. der Strusbek, "Basler AG-global manufacturer of digital cameras," *Microsc. Today*, vol. 26, no. S1, p. 6, Mar. 2018, doi: 10.1017/S1551929518000068.
[81] S. Sharifian, A. Homaei, R. Hemmati, and K. Khajeh, "Light emission miracle in the sea and preeminent applications of bioluminescence in recent new biotechnology," *J. Photochemistry Photobiol. B, Biol.*, vol. 172, pp. 115–128, Jul. 2017, doi: 10.1016/j.jphotobiol.2017.05.021.
[82] D. Celinskis, N. Friedman, M. Koksharov, J. Murphy, M. Gomez-Ramirez, D. Borton, N. Shaner, U. Hochgeschwender, D. Lipscombe, and C. Moore, "Miniaturized devices for bioluminescence imaging in freely behaving animals," in *Proc. 42nd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2020, pp. 4385–4389.
[83] T. Arias, A. Tran, J. Breaud, J. P. Fournier, A. Bongain, and J. Delotte, "A prospective study into the benefits of simulation training in teaching obstetric vaginal examination," *Int. J. Gynecol. Obstetrics*, vol. 133, no. 3, pp. 380–384, Jun. 2016, doi: 10.1016/j.ijgo.2015.08.028.
[84] V. Subedha, M. Purushothaman, R. Tinakar, and S. Sunaichandran, "Under water and underexposed image enhancement via image reduce hazing algorithm," *Int. J. Sci. Res. Eng. Trends*, vol. 6, no. 2, Apr. 2020.
[85] M. Tuba, M. Jordanski, and A. Arsic, "Improved weighted thresholded histogram equalization algorithm for digital image contrast enhancement using the bat algorithm," in *Bio-Inspired Computation and Applications in Image Processing*, X.-S. Yang and J. P. Papa, Eds. New York, NY, USA: Academic, 2016, pp. 61–86.
[86] M. Rela and S. N. Rao, "Comparative analysis of image enhancement techniques applied to CT liver image," *Int. J. Eng. Technol.*, vol. 7, no. 3, pp. 285–289, 2018.

TEMITOPE O. TAKPOR (Graduate Student Member, IEEE) received the B.Eng. degree in computer engineering from Covenant University, Ota, Ogun State, Nigeria, in 2008, and the M.Sc. degree in communications engineering from Durham University, Durham, U.K., in 2009. She is currently pursuing the Ph.D. degree in information and communication engineering with Covenant University.

From 2012 to 2015, she was an Assistant Lecturer with the Department of Electrical and Information Engineering, Covenant University. Since 2015, she has been a Lecturer II with the Department of Electrical and Information Engineering, Covenant University. She is very passionate about enhancing the health and well-being of people, especially maternal, newborn, and child health (MNCH) through innovative digital health technologies and medical devices. Her research interests include biomedical engineering design, health innovation, medical devices, maternal, newborn and child health (MNCH), biomedical imaging and image processing, computer vision, deep learning, e-health, wearables, telemedicine, and the Internet of Things.

Mrs. Takpor is a Graduate Student Member of EMBS. She is a member of the Computer Vision Foundation (CVF), the International Association of Engineers (IAENG), and the Nigerian Society of Engineers (NSE). She is a member of the IoT-Enabled Smart and Connected Communities (SmartCU) Cluster and the Advanced Signal Processing and Machine Intelligence Research (ASPMIR) Cluster, Covenant University. She was selected to attend the 2023 IEEE EMBS-SPS International Summer School on Biomedical Imaging. She was a recipient of the African Biomedical Engineering Mobility (ABEM) Scholarship Grant as a Visiting Ph.D. Student to the University of Cape Town, South Africa, in 2019. She was nominated as one of the Challenge Grant Winners to make a poster presentation at the Facebook AI 1st Workshop on Computer Vision for Global Challenges (CV4GC) at the IEEE Conference on Computer Vision and Pattern Recognition (CVPR), in 2019. She received the Best Paper Award from the International Conference of Computer Science and Engineering, which was presented at The World Congress on Engineering (WCE) 2014 London, U.K., 2–4 July 2014.

ADEREMI A. ATAYERO (Member, IEEE) received the Ph.D. degree in communication engineering from the Moscow State Technical University of Civil Aviation, in 2000.

He was the 5th Vice-Chancellor for Covenant University, Ota, Nigeria, from 2016 to 2020. He is currently a Professor of communication engineering. He is also the Head of the IoT-Enabled Smart and Connected Communities Research Cluster, Covenant University. He is a passionate educationist at the vanguard of the transformation in African Higher Education. He has progressive academic leadership experience in developing team members and collaborating regionally and globally to maintain a competitive edge in world-class education. He is recognized for contemporary multidisciplinary academic research with a special focus on wireless/mobile communications, the Internet of Things (IoT), and smart cities. He has published over 150 scientific papers in international peer-reviewed journals and proceedings.

Dr. Atayero is a fellow of the Science Association of Nigeria. He is a Senior Research Fellow of IARSA. He is a National Research and Education Network Ambassador of the West and Central African Research and Education Network. He received the Distinguished Communications Engineer's Award of Excellence from NIEEE. He is a COREN Registered Engineer.

EMMANUEL ADETIBA (Member, IEEE) received the Ph.D. degree in information and communication engineering from Covenant University, Ota, Nigeria.

He was the Director of the Center for Systems and Information Services (ICT Center), Covenant University, from 2017 to 2019. He is currently the Deputy Director of the Covenant Applied Informatics and Communication Africa Centre of Excellence (CApIC-ACE) and the Co-PI for the FEDGEN Cloud Infrastructure Research Project with the Center (World Bank funded). He is also the Founder and a Principal Investigator of the Advanced Signal Processing and Machine Intelligence Research (ASPMIR) Group. He is also a Full Professor and the incumbent Head of the Department of Electrical and Information Engineering, Covenant University. He is also an Honorary Research Associate with the Institute for System Sciences, Durban University of Technology, Durban, South Africa. He has received several grants and research funds from reputable bodies, such as the World Bank, the France Development Agency (AFD), the U.S. National Science Foundation, the Durban University of Technology in South Africa, the Nigeria Communications Commission, and hosts of others. He has authored about 100 publications in Scopus-indexed journals and conference proceedings. His research interests include machine intelligence, software-defined radio, cognitive radio, biomedical signal processing, cloud federation, and EduTech.

JOKE A. BADEJO (Member, IEEE) received the Ph.D. degree in computer engineering from Covenant University, Nigeria, in 2015.

She was a Senior Lecturer and the Coordinator of the Computer Engineering Program, Department of Electrical and Information Engineering, Covenant University. She is currently a Faculty Member of the Covenant Applied Informatics and Communication Africa Centre of Excellence (CApIC-ACE), a World Bank ACE-IMPACT Centre, Covenant University. She is also a Co-Investigator on a World Bank ACE-IMPACT Project targeted at developing a federated genomics cloud infrastructure for precision medicine in Africa. She has also been actively involved in the Covenant University Data Analytics Cluster (CUDAC), which supports data-driven decision-making at the university. She enjoys being an academic and loves contributing impactful and cost-effective solutions to current societal engineering problems in Africa. With more than a decade of computing research, teaching, and leadership experiences, she has published over 40 papers in reputable journals and conference proceedings. Her research interests include biometrics and biomedical image analysis, machine (deep) learning, large-scale data analytics, software engineering, and cloud computing.

Dr. Badejo is a member of the Council for the Regulation of Engineering in Nigeria and the Institute of Electrical and Electronics Engineers. She received the AfricaConnect2/WACREN International Travel Grant for TNC18, Trondheim, Norway, in 2018.