A CNN-Driven Near-Infrared Vein Visualization: Affordable Solutions for Diverse Clinical and Resource-Limited Settings

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Abstract: Venous access is a perilous defy for the pathological technician who does several attempts for collection of blood samples. The attempts, which are failed, can lead to the discomfort to the patient, increase the procedural stretch, and also to the high-risk impediments. These research generosities the design and implementation of a portable vein viewer device, that is cost effective solution for employing the near-infrared (NIR) imaging technology, aiming to enhance the vein-visibility during the vein-puncture. The scheme exploits a RaspberryPi4 Model-B, for the real-time image processing, 750 nm infrared illumination and an IR-sensitive camera to capture various patterns of the vein. As per the results obtained from the setup, the de-oxygenated hemoglobin in the veins enthralls the NIR light. This generates a contrast with the adjoining tissues. This divergence is further processed by Open-CV algorithms with the inclusion of grayscale conversion, Gaussian-blur, adaptively thresholding, and contrast-enhancement. After this processing, the vein map is demonstrated on a 3.2-inches LCD screen. This can be used by the pathologists or the clinicians with indistinct conjuring up of the subcutaneous veins. The method suggested in this research clearly demonstrates a substantial potential for the 'first-attempt success' for the blood draws and intra venous insertions, which was highly painful, specifically for children, geriatric, obese, and dark-skinned patients. Apart from the clinical applications, the method also offers utility in biometric authentication and forensic science, due to its affordability and portability, and make it most suitable for hospitals and clinics with resource-limited healthcare settings. Future augmentations of this research include amalgamation of AIML for the automations in the vein detection, wireless connectivity, and augmented reality overlays. This would position the suggested setup as a transformative contrivance in the healthcare centers and blood sample collection centers.

Keywords: — Near-Infrared Imaging (NIR), Vein-Visualization, Biomedical Image Processing, Non-Invasive Healthcare Devices, Venipuncture Assistance Technology

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1. INTRODUCTION

Venous access is one of the most perplexing trials and the contraption at the pathology, specifically, the blood sample collection centers. As far as the humdrum blood sampling to intravenous (IV) therapy is concerned, the ability to localize and puncture the respective veins precisely becomes critical for the children, geriatric, obese, and the patients with dark-skin, Secondly, the procedure of vein-puncture is difficult for the pathologists or the clinicians, for the patients with multifarious anatomical as well as physiological conditions. Almost 40% of patients face the problem of difficult venous access, that leads to several disastrous attempts. Procedure time, patient discomfort, and high risk complications including hematoma, phlebitis, or infection are increased due to the multiple attempts of venous puncturing. Routine procedures for the vein detection based on normal visual examination or palpation. Medical professional who collects the blood samples rely on his experience, perceptible response, and visual prompts to identify the vein to be punctured. Sometimes, their experience fails and require many attempts due to individual-specific factors like obesity, dehydration, dark skin pigmentation, aging, or pediatric physiology. Since the veins could be difficult to locate, they keep on repeated needle insertions and increase the patient's anxiety. These challenges motivated us to provide an innovative, reliable, non-invasive, and real-time visualization of venous structures, that can augment the vein visibility and mend the effectiveness of venous access actions.

The previous study carried through [1-10] or the overall collective research clearly indicates that there is noteworthy progress in the field of vein imaging, vein visualization, and the related therapeutic applications, straddling diagnostic scanners, low-cost imaging schemes, and the radical techniques related to laser coagulation.

The study [1] claims for a diagnostic scanner, aiming for detecting the apparent veins using near-infrared (NIR) imaging region and the accuracy in recognizing the venous structures by using the captivation properties of de-oxygenated hemoglobin, its portability making it suitable for the clinical and resource-limited settings as well, offering 1st -attempt success rates in the vein-puncture. The research [2] explores the automation in endo-vassal laser coagulation through the venous bed-visualization, assimilating imaging with programmed laser arrangements to augment the precision, reduce the operator reliance, thereby improving the patient's safety, emphasizing the probable combination of visualization with robotics for minimum invasive vascular therapy. The work [3] focus on evolving the visualization of veins method using Raspberry Pi, IR cameras, and Open-CV algorithms, the system provided real-time. Results demonstrated the unsuccessful multiple attempts of veni-puncture in pediatric and geriatric patients in rural clinics. The research [4] presents a basic method of vein viewer emphasize the affordability and usability, through NIR illumination and the basic image processing for vein visualization. The work [5] focus on use of water, incorporates the process of heat transfer during endo-venous laser coagulation demonstrate that the lopsided heat-distribution provides efficacy in treatment by optimizing the laser parameters to minimalize the tissue damage and ensure the effective vein closure. [6] vivo the experiments to optimize laser sceneries in the endo-venous procedures balancing the energy delivery with the tissue response, thereby plummeting the complications including burns and incomplete occlusion. [7] use a 1940 nm laser for saphenous vein occlusion through greater absorption by water and hemoglobin at the same wavelength, resulting in efficient vein closure. [8] demonstrates the heftiness of the finger vein recognition as one of the biometric modality in the secure authentication systems. The research [9] focus on K-means hashing method of affinity-preserving for enhancing the efficient vein retrieval, improved retrieval accuracy. Overall Synthesis collectively accentuate the potential of NIR imaging, cost effective hardware, and progressive laser technologies in vein visualization and treatment. Diagnostic scanners and vein viewers enhance clinical efficiency and patient comfort, while laser coagulation research refines therapeutic precision. Parallel advances in biometric vein recognition highlight the versatility of vein imaging beyond healthcare, extending into security and forensic applications. Together, these findings establish vein visualization as a multidisciplinary frontier bridging medicine, engineering, and information technology.

Problem definition for this research moves around the most conjoint tasks in the healthcare system, the venous access for blood sampling and intravenous (IV) cannulation, locating suitable veins has always been a tenacious challenge. Data set is generated from the conventional methods relying on visual inspection and palpation resulting in the failures during vein-punctures, particularly in the patients with obesity, pediatric and elderly individuals, and also those patients with dark skin tones. often leading to multiple failed attempts, causing patient discomfort, procedural delays, and increased risk of complications such as hematoma or infection. Since the commercial vein visualization devices are affluent, bulky, and unreachable in resource-limited settings, a cost-effective, handy, and user-friendly elucidation that can augment the vein visibility in real time and improve the vein-puncture success rate is required to be developed. Among many technological advancements in medical imaging and diagnostics, vein visualization techniques need more attention. Researchers are referring Near-infrared (NIR) imaging as one of the most operative approaches. NIR light in the range of 700–900 nm is able to penetrate the skin and simultaneously react with blood and contiguous tissues differently. De-oxygenated hemoglobin in the veins absorb whereas the adjacent tissues reflect the Near-infrared light. This create a contrast, which can be captured by infrared-sensitive cameras, processed and displayed as a real-time record of the venous network. This help the clinicians to recognize appropriate puncture sites with greater exactitude. Accu-Vein and Vein-Viewer have confirmed the clinical utility of NIR imaging by projecting the processed vein images on the patient's skin, presenting an augmented real time, first-attempt successful experience. However, in spite of their efficacy, existing commercial vein visualization schemes are found expensive, bulky and unavailable in many resource-limited healthcare centers, including rural hospitals.

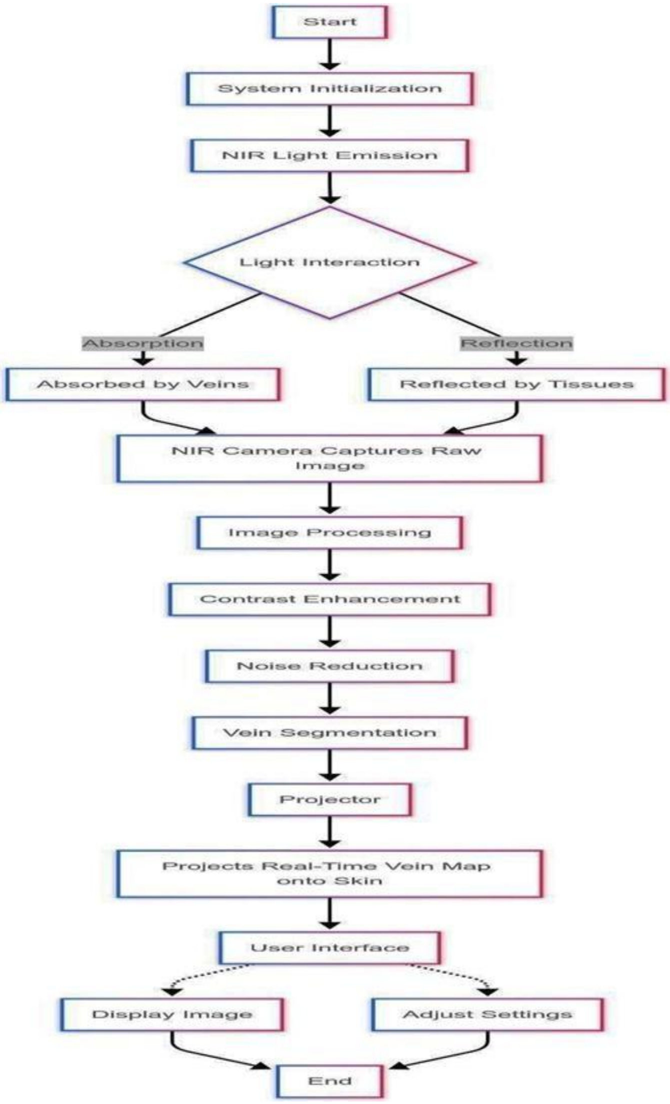
2. OBJECTIVES

Objectives of this research are

- To design and develop a structurally comprehensive, portable, cost-effective near-infrared (NIR) vein visualization system that enhances the visibility of peripheral veins during venipuncture procedures.
- To implement and optimize image processing algorithms that effectively enhance contrast between veins and surrounding tissues in real-time.
- To evaluate the technical performance of the device through quantitative metrics including vein detection accuracy, imaging depth, and system response time.
- To assess the clinical efficacy of the Vein Viewer in improving first-attempt success rates during venipuncture across diverse patient populations (pediatric, elderly, obese, and patients with dark skin tones).
- To investigate the integration capabilities of the system with existing healthcare workflows and infrastructure.

3. PROPOSED METHOD FOR VEIN VISUALIZATION:

The incongruence between accessibility and the actual clinical requirement has motivated us to explore cost-effective, portable, vein visualization system to bridge the gap, confirming reasonably advanced technology. By leveraging open-source hardware and software platforms including Raspberry Pi and Open-CV, it was possible for us to design technically robust and economically sustainable vein viewers with diverse settings, from modern hospitals to rural clinics. Flow diagram of the proposed Vein Visualization system is given in Fig.1



A framework showing the structured sequential process, specifically designed to enrich the venous visibility based on Near-Infrared (NIR) in real-time can be viewed as follows. First step is 'Initialization', where 750 nm IR-LEDs are used to irradiate the patient's hand inside a compartment. Care is taken to minimalize the peripheral light intrusion. A No-IR camera, which is IR-sensitive, is used to capture the reflected light. This exploit the immersion properties of de-oxygenated haemoglobin to differentiate veins from adjacent tissues. RaspberryPi4 Model-B process the captured frames by means of image enhancement through grayscale conversion for enhanced contrast, Gaussian-blur for noise reduction, adaptive thresholding for vigorous vein segmentation. CLAHE is used to provide local contrast enhancement. The processed metaphors are sized to fit in the '320×240' resolution of a 3.2-inch LCD display. This display gets continuously updated and provides a live video feed of the vein-patterns. The resulting real-time conception with capability of an augmented reality helps in identifying the corresponding vein-puncture sites with better exactitude and composure. Overall setup supports in developing training patterns continuously, stowed images can be used in machine learning with improved detection accuracy, in turn, provides adaptive intelligence, a cost-effective, portable, and user-friendly hardware efficiency for Vein visualization. Vein Viewer Setup is shown in Fig.2

Fig.2 (a) Vein Viewer Setup

Fig.2 (b) CNN based Vein Viewer Setup

4. CLINICAL SIGNIFICANCE

The clinical insinuations of the method and apparatus devised through this research is insightful, and is highly useful in all the cases, including pediatric care, where the child's veins are very small and fragile resulting in the complications in the process of venipuncture. Using our proposed model, a vein viewer can lessen the trauma and anxiety of the child by reducing repeated needle-sticks, and can get the result in one stroke only. In geriatric or elderly populations, due to skin and tissue changes, vein identification is less protuberant because of the aging factor. In this circumstance, our suggested device can enhance the visibility of veins and mend the vein detection success. In case of obese patients, the subcutaneous intravenous fat obfuscates veins, infrared type imaging can divulge deeper venous structures, those are otherwise invisible for the pathology or clinical person. For the patients with dark skin pigmentation, the visual cues are inadequate. In this case the NIR imaging can be the best technique for vein puncture location identification. In emergency services rapid Intra-Venous access is perilous, the proposed portable vein viewer can save the time and increase the success rate. Table 1 shows the Clinical Justification of the Proposed Vein Viewer for clinical scenario, challenges in veni-puncture, solution and its impact provided by the proposed device and outcome. Beyond the above mentioned clinical applications, the proposed method of vein visualization can be proved to be advantageous in other fields including biometric authentication and forensic science, since the vein patterns are unique and can serve as the secured identifiers. In forensic investigations, vein imaging can be used to identify the person. Other applications can also incorporate the versatility and influence of vein visualization systems, as given in Table 1.

Table 1 Outcome and Impact analysis

Clinical Scenario	Challenges in Venipuncture	Proposed Device Contribution	Expected Outcome	Broader Healthcare Impact
Pediatric Care	Small, fragile veins; high risk of multiple needle-sticks; increased trauma and anxiety.	Provides enhanced visualization of tiny veins using NIR imaging; reduces repeated attempts.	Minimizes trauma, reduces anxiety, improves first-attempt success rate.	Enhances patient satisfaction, reduces procedural time, lowers costs from repeated interventions.
Geriatric Patients	Aging skin and tissue changes make veins less prominent and harder to detect.	Enhances vein visibility through contrast imaging; compensates for reduced vein protuberance.	Improves detection accuracy, reduces complications, increases patient comfort.	Improves workflow efficiency, reduces risk of complications, lowers hospital resource utilization.
Obese Patients	Subcutaneous fat obscures veins, making palpation and visual cues unreliable.	Infrared imaging penetrates deeper tissues, revealing venous structures invisible to the naked eye.	Enables reliable vein detection, reduces failed attempts, improves clinical workflow.	Reduces costs from repeated attempts, improves staff efficiency, enhances equity of care delivery.
Dark-Skinned Patients	Visual cues inadequate due to pigmentation; veins less visible to clinicians.	NIR imaging provides clear contrast between veins and surrounding tissues regardless of skin tone.	Ensures equitable care, improves success rates across diverse populations.	Promotes inclusivity in healthcare, reduces disparities, improves patient trust and satisfaction.
Emergency Services	Rapid IV access critical; delays can be life-threatening; traditional methods waste time.	Portable vein viewer offers real-time visualization, enabling faster venous access in critical situations.	Saves time, increases success rate, enhances emergency response efficiency.	Improves survival rates, reduces emergency costs, streamlines critical care workflows.

5. IMAGE PROCESSING IN VEIN VIEWER THROUGH CNN

The proposed model of vein visualization has been integrated with Convolutional Neural Networks (CNNs). Techniques used for grayscale adaptation, thresholding and histogram equalization can be used to provide basic levels of the contrast, but they fail with capriciousness in skin tones and tissue thickness of the patient. CNN can automatically learn the categorized topographies from the infrared, i.e. IR vein images, enable the robust and adaptive detection of vein structures. In the proposed model of the Vein Viewer, IR images are captured by the Raspberry Pi, NoIR-camera is trained with the varied datasets of the vein patterns. Convolutional layers decrease the dimensionality and preserve the essential characteristics of veins. Consequent layers of CNN learn the higher-order representations, extricate the veins from noise and contextual tissues leverage the ReLU activation functions and optimize through batch normalization. After preprocessing, the output is displayed on the LCD screen, which is in real time, and ready to serve for the vein-puncture process. This computationally intelligent approach is easy for the clinicians for further process, since they can view the clear visualization of subcutaneous veins. Convolutional deeply learnt model keeps on learning and the stored vein images can be used retrain the CNN model, further improving the detection accuracy.

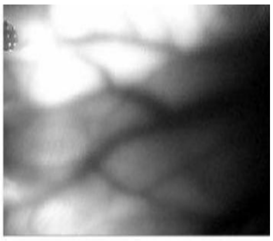


Fig.5 (a) Preprocessing stage

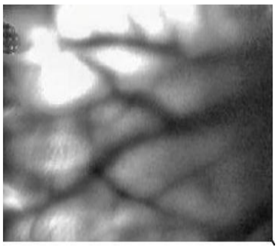


Fig.5 (b) Feature extraction

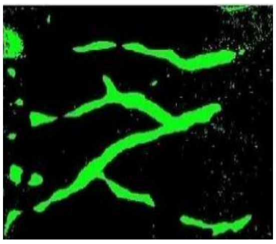


Fig.5 (c) Output stage

Figures 5(a), 5(b), and 5(c) exemplify the chronological workflow of image processing in the Vein visualization using Convolutional Neural Networks (CNN). Figure 5 a portrays the pre-processing stage, where the IR, i.e. infra-red vein images endure conversion in grayscale, Gaussian-blur, and an adaptive thresholding to enrich the contrast. Figure 5 b displays the CNN architecture, with convolutional and assembling layers extracting the features of the vein. It has been observed that there is significant reduction in noise and dimensionality. Figure 5 c is the final stage, where higher-order representations learnt by the CNN map the vein patterns with greater clarity. Display is obtained in real time on the LCD screen. This enables the clinicians to visualize the intravenous structure or the veins with better accuracy.

6. CHALLENGES AND FUTURE DIRECTIONS

While the proposed system demonstrates significant promise, challenges remain. External lighting conditions can interfere with image quality, necessitating enclosed chambers or controlled illumination. Variability in skin types and thickness may affect detection accuracy, requiring adaptive algorithms. For ensuring clinical reliability if high-resolution images are required, then there will be more computational complexity thereby reducing the processing

speed. If these challenges are properly addressed, we can optimize the system performance.
Future scope of this research could be the integration of wireless model to enable transmission of the processed images to be viewed at remote place. Incorporation of Augmented reality can improve the projection of the vein patterns in the live camera feeds. Image quality can be enhanced through high resolution cameras and the progressive sensors. Self- organized deep models can be developed to finely tune automation process the cataloguing the vein finding more efficiently. These novel approaches could expand the abilities of clinicians, through the indispensable tools in modern healthcare.

7. CONCLUSION

Through this research, we have designed and implemented a structurally comprehensive, portable, cost-effective near-infrared (NIR) vein visualization system that enhances the visibility of peripheral veins during veni-puncture procedures.
We have successfully implemented and optimized the image processing algorithms to effectively enhance the contrast between veins and surrounding tissues in real-time. The technical performance of the device is evaluated through the quantitative metrics, typically including the vein detection accuracy, imaging depth, and system response time. The clinical efficacy of the Vein Viewer in improving first-attempt success rates during venipuncture across diverse patient populations (pediatric, elderly, obese, and patients with dark skin tones) has been assessed and investigated the integration capabilities of the system with existing healthcare workflows and infrastructure.

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