A novel image fusion approach for improving vessel visibility in surgical filler injections

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Abstract

The occurrence of adverse events caused by intravascular injection or vascular compression of filler material remains a persistent concern for surgical filler injection. In order to enhance the visibility of facial vessels and make the injection procedure safe, this paper reports a simple yet effective image fusion approach that combines simultaneously captured visible and near-infrared images to produce vessel-highlighted effects. The visibility enhancement of vessel details involves applying a customized sharpening filter to the NIR image prior to merging it with the color facial. The validation of the fused images is conducted by employing quantitative objective metrics of image quality and clinical efficiency in the identification of vessels. The experimental results demonstrate the proposed approach can efficiently generate discernible impression of vessels with color and texture realistically persevered, and therefore contributes to augment the safety and precision of surgical planning or guidance in filler injections.

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Abstract: The occurrence of adverse events caused by intravascular injection or vascular compression of filler material remains a persistent concern for surgical filler injection. In order to enhance the visibility of facial vessels and make the injection procedure safe, this paper reports a simple yet effective image fusion approach that combines simultaneously captured visible and near-infrared images to produce vessel-highlighted effects. The visibility enhancement of vessel details involves applying a customized sharpening filter to the NIR image prior to merging it with the color facial. The validation of the fused images is conducted by employing quantitative objective metrics of image quality and clinical efficiency in the identification of vessels. The experimental results demonstrate the proposed approach can efficiently generate discernible impression of vessels with color and texture realistically persevered, and therefore contributes to augment the safety and precision of surgical planning or guidance in filler injections.

Keywords: Image fusion; near infrared light; visualization enhancement; filler injection

1. INTRODUCTION

Soft tissue filler injections have experienced a notable increase in demand in recent years, particularly for facial rejuvenation, contouring, and volumizing, owing to their efficacy and cost-effectiveness. In the United States, the number of procedures performed in 2021 reached a total of 1.8 million, marking a significant increase of 42%[1]. While facial fillers are widely acknowledged for their cosmetic enhancement capabilities, the occurrence of associated adverse events remains a persistent concern, stemming from both the filler substance itself and the injection techniques employed. In severe cases, intravascular injection or vascular compression of the filler material can result in skin necrosis or even blindness[2][3]. Apart from the filler substance, injection-related complications primarily arise from the complex nature of facial vasculature and the insufficient injection skill of relevant clinicians[4]. In reality, facial vasculature exhibits asymmetrical distribution with no regular pattern, both at the individual and population levels[5]. It is reported that 61% of experienced trainers encountered vascular complications in their own practice, and 28.6% of participating dermatologists documented at least one occurrence of vascular occlusion[6].

To cope with the complexity of facial vasculature and mitigate the risk of intravascular injection for minimizing potential damage to underlying tissues or organs, what physicians do now is to accumulate their experience in injection techniques and develop a comprehensive understanding of facial anatomy[7]. This may help them to build a clear roadmap for precisely locating the needle tip in relation to those vasculature structures with potential risks, thereby minimizing the probability of intravascular injection. However, visual identification of the location of either the tip or the vessels during the injection process presents challenging or impossible, as a visual warning becomes lack when the needle enters into the tissue unapparent to human eyes. In order to mitigate the likelihood of the intravascular injection, physicians have explored various technical approaches, such as needle redesign[8] or ultrasound-guided operation[9][10]. While both methods offered some degree of assistance in avoiding the deep vessels during injection, the use of double needles introduces invasiveness, and ultrasound imaging may fail to detect those vessels too shallow for ultrasound probes but too deep for visual inspection[11]. Moreover, the continuous application of varying pressure and orientation of ultrasound probes on the targeted skin can complicate the ultrasound navigation process. The pressure exerted may displace the vessels intermittently, and the operator or assistants must keep interpreting the scanned images of the vasculature on the screen in order to update the precise location of the needle and vessels continuously[12].

Previous studies have found that optical-based techniques offer a non-contact means observing the distribution of blood vessels on superficial tissue surface. Particularly the deep penetration capability of near-infrared
(NIR) radiation and unique absorption properties of blood chromophores like hemoglobin makes the appearance of veins or arteries differentially in comparison to the surrounding skin tissues\textsuperscript{[13]} \textsuperscript{[14]}\textsuperscript{[15]} \textsuperscript{[16]}\textsuperscript{[17]}. Therefore, the optical-based methods have been utilized to visualize the distribution of blood vessels for facilitating the procedures such as venous puncture and intravenous cannulation\textsuperscript{[15]} \textsuperscript{[16]} \textsuperscript{[17]}. However, the deployment of these approaches generally requires the distance between the optical sensors and the injection site to remain constant so that the vessel structure captured can be projected back to the regions being investigated. The presence of this requirement places constraints on both the dimension of working space and the level of freedom afforded to the surgical operator in terms of adjusting the position of the subject during the procedure, thus posing a significant challenge to the successful execution of filler injection. Meanwhile the solely employment of NIR image containing fewer color textures of the scene would degrade the perception on the regions being operated. To fully make use of the optical imaging approach for the task of filler injection, the complementary visible and NIR information need to be used together so that the appearance of tissue surface as well as the vessel structure underneath skin tissue would be both visible in an augmented manner.

Combining imaging information from different sources into a new form was known as image fusion which is normally designed to achieve better visual effects for a wide range of applications like remote sensing and tumors detection\textsuperscript{[18]} \textsuperscript{[19]}\textsuperscript{[20]} \textsuperscript{[21]}. Some algorithms have been developed to combine visible and NIR information to achieve desired color representation that is visually appealing to human perception. Among them, the RGB color mode is typically transferred into alternative representations with luminance and chroma components so that any modification to the luminance can be made without affecting original color components. Then the fusion methods tended to use NIR images to replace the luminance layer of regular colour images\textsuperscript{[22]} \textsuperscript{[23]} \textsuperscript{[24]} \textsuperscript{[25]} \textsuperscript{[26]}. This process can generate a vivid and well-contrasted effect when reproducing the scenes like outdoor and human skin\textsuperscript{[22]}. As the surface reflectance of scenes is wavelength dependent, it is inevitable that there will be inconsistencies between the NIR image and the luminance component within the visible spectrum. Moreover, the NIR images frequently exhibit degradation in terms of texture loss or blurriness, primarily attributed to the prevailing scattering effect resulting from the interaction between long-wavelength NIR light and the surface of the scene. In order to solve this problem, some fusion algorithms purposely made use of the difference between them to adaptively improve the visibility and contrast of images of those special conditions like haze and mist\textsuperscript{[23]} \textsuperscript{[24]} \textsuperscript{[25]} \textsuperscript{[26]}. Additionally, others have explored alternative strategies, such as the utilization of various edges-preserving smoothing filters or the transformation of the problem into an optimization process, in order to address the issue of color or texture degradation in image fusion processing\textsuperscript{[23]} \textsuperscript{[24]} \textsuperscript{[25]} \textsuperscript{[26]} \textsuperscript{[27]} \textsuperscript{[28]}. The aforementioned strategies have been developed to address the issue of image deterioration with fusion, specifically targeting the enhancement of color perception in outdoor scenes. However, most of these approaches are inherently time-consuming as the iterative calculations involved in solving optimization problems. Nonetheless, the need to update vessel structures in real-time for filler injection necessitates the availability of models capable of efficiently fusing images of biological tissues. This paper presents a novel approach that effectively integrates facial images captured under visible and NIR spectra, resulting in improved visibility of the facial vessel structure that is of utmost importance in filler injection. Specifically, the proposed approach first simultaneously captures the visible and NIR images of interested facial region. Then the vessel structures are highlighted via an effective sharpening mechanism on the NIR images before they are fused with the visible color images. Finally, the enhanced results are integrated with the decomposed chroma component of the visible images to produce an enhanced visual impression of the region receiving filler injection. The effectiveness of the proposed approach is validated through a comparative analysis with conventional image fusion techniques employing quality evaluation metrics for fusion images and efficiency feedback provided by clinicians.

2. METHOD AND MATERIALS

2.1 Vessels highlighted for image fusion

Figure 1 illustrates the schematic of two image fusion strategies, namely conventional NIR colorization (CNC) approach and our proposed highlighted NIR colorization (HNC) approach. The CNC firstly decomposes the white balanced visible image 1(b) into YUV format (Y layer represents luminance and UV layers represent...
chroma) and then the decomposed luminance layer is directly swapped with the captured NIR image 1(c). The new combination of the NIR image and the decomposed UV layers are finally converted back to the form of RGB color image and presented in Fig. 1(f). The NIR image in Fig. 1(c) exhibits a certain level of blurriness attributed to the prevalent scattering of NIR light as it interacts with the skin tissue. Consequently, this blurriness adversely affected the quality of the fused color image in Fig. 1(f), resulting in a diminished visibility of the vessel structure. To allow the vessels revealed with more visibility for clinical interventional procedure, the proposed HNC chooses to process the captured NIR images before they are used to replace the decomposed luminance layer Y.

The HNC firstly employs a high-pass filter to remove the blurriness from the NIR image and sharpen the spatial details such as vessel structure and other detailed anatomical textures. The choice of the filter’s kernel size $k$ is based on the minimal vessel to be detected and the acceptable level of degradation observed in the resulting image. The larger $k$ tends to improve the visibility of small features like vessel and hair structure; however, it will produce glowing artifacts at the boundaries of these small structures, and entail a greater computational burden to perform image filtering as well. It has been found the value of $k$ can be adjusted between 20 and 30 to achieve the best highlighting of vessels for our experimental image data. To mitigate the glowing artifacts caused by high-pass filter, a Gaussian smooth filter is applied subsequently to average out those extreme values and suppress the details wrongly enhanced. Although more sophisticated filters such as the bilateral filter can be used to remove the glowing artifacts, it may take minutes to process one image\textsuperscript{[29]}. On the contrary, the employed Gaussian smooth filter is characterized by the separability and the quad-symmetry, making it well suited for real-time image processing applications. After the filtering processing, a result with vessel enhanced can be found from Fig. 1(e). Note that the implementation of the high pass filter and Gaussian filter are convolution-based calculation that can be implemented via parallel computing.

Once the NIR image has undergone enhancement, resulting in improved visibility of vessel structures, it is ready to swap with the decomposed luminance layer of color image. Due to significant color bias observed in the color images captured by the experimental camera, they will be corrected before passing for the following processing. Fig. 1(b) illustrates the outcome of the white balance correction procedure applied to the original captured color image 1(a). The corrected color image is then decomposed into the YUV color space. The YUV color space is used because it closely matches with the human visual perception on color, and demonstrates good compatibility and compression efficiency for a wide range of broadcasting devices and software. Similar to the conventional fusion approach, the swapping implemented between the enhanced NIR image and decomposed luminance layer Y does not alter the color layers UV of original images. Finally, the swapped luminance layer and color layers are combined together and converted back to the RGB representation as shown in Fig. 1(g).

### 2.2. Quality assessment of image fusion

In order to assess and refine the proposed fusion algorithm, the data acquired from real scenarios are used to evaluate the performances of the conventional and new proposed fusion methods. Several established quality assessment criteria, drawing upon concepts from information theory, image structure similarity, and human visual perception, have been adapted to provide quantitative evaluations of the performance of NIR and visible image fusion methods\textsuperscript{[30]}. In parallel, the perspectives from clinicians have been sought to conduct subjective evaluations on the clinical value of the image fusion techniques.

Totally there are six objective quality criteria used to evaluate the performance of the proposed image fusion approach including entropy (EN), average gradient (AG), spatial frequency (SF), mutual information (MI)\textsuperscript{[31]}, feature mutual information (FMI)\textsuperscript{[32]} and visual information fidelity (VIF)\textsuperscript{[33]}. EN, AG and SF measure the information content and texture details embedded within an image, i.e. the overall amount of general information and gradient distribution present within a fused image. MI and FMI measure the amount of
image information and feature information transferred from source image to fused image respectively. VIF quantifies the visual information fidelity of an interested image, which is normally consistent with human visual perception in quantifying either luminance or color distortion of fused image. These objective metrics facilitate a comparative evaluation and assessment of the performance of the CNC and HNC image fusion approaches from different perspectives.

2.3. Clinical assessment of image fusion

The objective assessment criteria can quantify the degree of information preservation or similarity between original and fused images; nevertheless, they do not provide any indication as to whether this similarity or difference has a positive or negative effect on the features that hold clinical significance. In order to evaluate the significance of image fusion for clinical purposes, experienced filler injection physicians are invited to delineate and count the number of vessels from the different sources including original color images with no enhancement and those enhanced by the CNC and HNC approaches. The amount of blood vessels identifiable and the efficiency in identifying the vessels within the images are compared for measuring the performance of image fusion approaches.

The intricate nature of facial vascular structures renders each distinct facial region susceptible to potential risks associated with surgical filler injection procedures[34]. In light of the alarming prevalence of blindness cases reported in the anatomical area known as the glabella, the forehead region has been selected as a prime candidate for the following clinical assessment[35]. This clinical assessment will serve as a complementary measure on the proposed fusion approach.

2.4 Experimental data collection

Fig. 2 shows the prism based multi-spectral camera (JAI’s AD-130GE) used to capture the broad-spectrum lights reflected from the interested regions on face. The prism splits the reflected light into two separated beams with one being directed towards a visible optical sensor and another being directed towards an NIR optical sensor. This enables a pair of aligned visible and NIR images acquired simultaneously as illustrated in Fig 1(a) and (c). One lamp consisting of NIR LEDs has been used as a supplementary light source to compensate the insufficient natural near-infrared flux present in natural lighting environment. The NIR LEDs are characterized by their 850 nm wavelength, which ensures adequate light penetration and efficient absorption by hemoglobin chromophores, thereby facilitating the enhanced visualization of vessel structures. A high-resolution machine vision Lenses (LINOS® MeVis-C) compatible with both visible and NIR spectra is used to collect lights with low distortion and adequate chromatic correction.

A cohort comprising ten Chinese adult volunteers who met the criteria for good health was enlisted to partake in the experiments, and informed consent was obtained from all subjects prior to participation in the study. To guarantee the reliability and consistency of experimental data, the physician captures ten sets of visible and NIR images of the forehead for each participant while the subject is properly positioned in front of the camera and light source.

3. RESULTS AND DISCUSSION

3.1 Quality of enhanced color images

Fig. 3 shows the distribution of average EN, SF, AG, MI, SMI and VIF values of 100 fused images by using CNC and HNC respectively. Compared to the CNC, the HNC method shows similar values in EN but larger value in AG and SF. This indicates the richness of information containing within the fused images from two approaches are very similar, while the salient gradient is a little bit more with the results from the HNC approach which exhibits the potential in enhancing the detailed texture. Meanwhile the CNC method demonstrates good performances in MI and FMI, which indicate that majority amount of color information has been successfully transferred from the original RGB images to the fused images when using the CNC
method. It is worth noting that the HNC image fusion approach, although not as effective in preserving color information as the CNC method, but conveys more saliency information which is crucial for vessel enhancement applications. The comparable metric of VIFs between two fusion approaches implies that the loss or distortion of color in the HNC approach is acceptable for human visual perception. Therefore, it can be concluded that the HNC generally perform well in preserving the color of original images as well as transferring desired detailed texture information including vessel structures.

The visual interpretation of the fused images reflects the similar findings from the above objective assessment. Fig. 4(a)-4(c) demonstrate the captured and fusion processed images of one subject’s forehead. It can be found that the vessel structure hidden underneath skin surface is virtually imperceptible in the original color images, but the corresponding fused images distinctly expose the structures. The HNC approach yielded more discernible impacts in revealing the architectural attributes of vessels, while the CNC exhibited constraints in accurately reconstructing intricate textures, particularly for diminutive or indistinct vessel structures. In addition to the vessels, the CNC fusion results exhibit blurring of other minor structures such as hair and pores due to the high penetrability of NIR light through these small structures. Nevertheless, the HNC approach enhances the visibility of these minor structures while minimizing color distortion and artifacts.

### 3.2 Clinical evaluation of vessel recovery

The performance evaluation of the fusion approaches in clinical settings involved a comparative analysis of the total count of discernible vessels in the original face color images, the fused images generated by the CNC and the HNC. Meanwhile the duration necessary for vessel marking and counting is reordered to assess the efficiency enabled by the fusion approaches. Three experienced physicians specializing in injection techniques performed the counting of blood vessels by following this procedure: initially identifying subsequent marking of all observable locations of vascular bifurcation or termination; subsequently labelling all visible blood vessels between each pair of marked points; and finally counting the total number of blood vessels. Fig. 4(d)-4(f) exemplify the results of marking and labelling of blood vessels. Table 1 lists the average number of vessels identified by three physicians for the original visible images and the processed images obtained from 10 experimental subjects. Additionally, it presents the average time spent on vessel counting and the resulting counting efficiency.

Table 1 Average vessel count, time, and efficiency of vessel enumeration by three physicians. Efficiency is expressed as the number of vessels accurately identified within a 10-second interval.
<table>
<thead>
<tr>
<th>Subjects</th>
<th>No. of vessels/counting time(s)</th>
<th>No. of vessels/counting time(s)</th>
<th>No. of vessels/counting time(s)</th>
<th>Efficiency of vascular counting</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIS</td>
<td>HNC</td>
<td>CNC</td>
<td>VIS</td>
<td>VIS</td>
</tr>
<tr>
<td>1</td>
<td>7/18.4</td>
<td>26/44.9</td>
<td>25/67.4</td>
<td>3.8</td>
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<td>2</td>
<td>0/9.5</td>
<td>7/20.9</td>
<td>7/30.6</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0/8.8</td>
<td>13/37.5</td>
<td>13/54.3</td>
<td>0.0</td>
</tr>
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<td>4</td>
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<td>10/27.1</td>
<td>10/42.9</td>
<td>2.9</td>
</tr>
<tr>
<td>5</td>
<td>0/7.3</td>
<td>9/33.5</td>
<td>9/44.1</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>4/20.4</td>
<td>19/46.7</td>
<td>19/65.6</td>
<td>2.0</td>
</tr>
<tr>
<td>7</td>
<td>0/13.0</td>
<td>4/26.4</td>
<td>4/36.9</td>
<td>0.0</td>
</tr>
<tr>
<td>8</td>
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<td>2/17.8</td>
<td>1/20.7</td>
<td>1.2</td>
</tr>
<tr>
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<tr>
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<td>2/14.4</td>
<td>10/29.0</td>
<td>10/34.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The results in Table 1 indicate that the visible images with no fusion processing exhibit inadequacy for locating or visualizing facial vessels due to the inherent limitations associated with low visibility and vessel contrast. In contrast, the utilization of NIR lighting conditions allows for the improved visualization of blood vessels beneath the facial skin. The CNC and HNC fusion approaches enhance vessel visibility and contrast, thereby conferring them a distinct advantage in vessel localization applications. Although both methods rely on the same NIR images, the HNC approach has not exhibited significant progress in terms of the total number of vessels identified, as compared to the CNC approach. However, the HNC approach outperforms the CNC approach in terms of the efficacy in marking and quantifying blood vessels. This highlights its potential in facilitating the locating and dynamic updating vascular structures during filler injection procedures.

### 3.3. Limitations and further work

A new image fusion strategy highlighting and incorporating NIR images has been demonstrated with the capability of improving vessel visibility. Non-ionizing and non-invasive NIR optical imaging also makes this approach safe and user-friendly. However, additional optimization is still necessary before deploying it for mitigating the complications and adverse events associated with filler injections in clinic.

As a preliminary experiment, only a limited number of volunteers have been recruited to carry out the experiments. To validate an optical imaging system for the application of filler injection, more data must be gathered to encompass the full range of diversity within the population and ethical considerations. Meanwhile, the customized image capturing and fusing system demonstrated the capability to improve the visibility of the vessel structures at facial regions. However, there is no mechanism to inform the depth and dimension of the detected vessels, which are useful to enhance the practicality of the fusion approach in guiding the injection procedures. Therefore, further investigations can be conducted to quantify the penetration capability and spatial resolution of the proposed NIR colorizing approach by utilizing tissue equivalent standard phantoms.

### 4. CONCLUSIONS

The occurrence of intravenous injection often causes the complication for filler injection operation. By taking advantage of the deep penetrability of NIR lights, a new image fusion approach has been proposed to integrate the visible color image and the NIR image to highlight the structure of facial blood vessels. Comparative analysis indicates that the newly introduced method surpasses the conventional image fusion approach in terms of preserving the perceivable vessel structure and retaining adequate color information. Moreover, the developed near-infrared image fusion approach offers rapid imaging and visualization capabilities, making it particularly suitable for those clinical applications requiring real-time localization and identification of vasculature, such as filler injection, the treatment of varicose veins and telangiectasia.
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CONFLICT OF INTEREST

The authors declare no financial or commercial conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCE


