Skin-Mimicking Phantoms for Assessing Performance of Emerging Photoacoustic Microscopy Devices

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Abstract

Photoacoustic microscopy (PAM) is an emerging hybrid technology that combines tightly focused optics and high-frequency ultrasonic detectors to achieve high resolution images of light-absorbing molecules such as hemoglobin or contrast agents. To streamline PAM regulatory evaluation and clinical translation, we developed tissue-mimicking materials (TMMs) with optical and acoustic properties simulating human dermis. Phantoms containing absorptive targets were fabricated from this TMM to demonstrate utility for image quality assessment (spatial resolution, maximum imaging depth).

Introduction

- **Photoacoustic Microscopy (PAM) is a rapidly emerging medical imaging modality with broad applications in dermatology, oncology, and vascular imaging.**
- **Commonly used test methods are not well-validated and standardized to support PAM device development, performance evaluation, and regulatory decision-making.**
- **Phantoms made from tissue-mimicking materials (TMMs) with biologically relevant properties and embedded targets are critical for objective image quality testing.**
- **Study Objectives: Develop a PAM-suitable TMM, construct image quality phantoms, and characterize performance of a custom PAM system.**

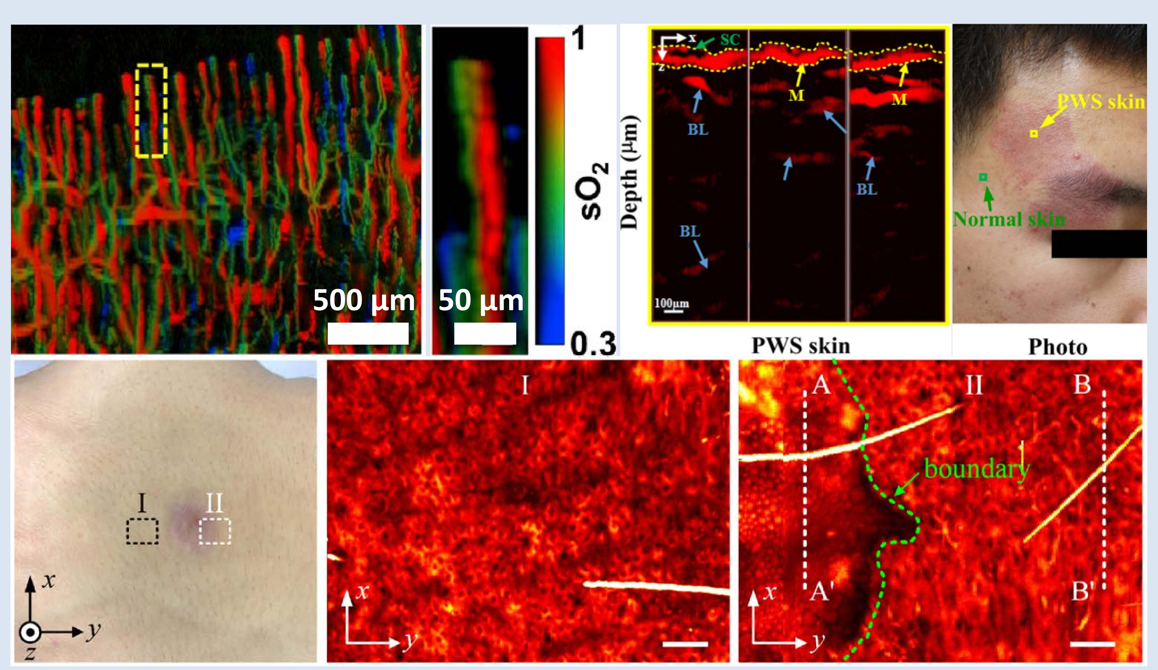


Figure 1. Top: PAM of nail-fold cuticle capillaries (left) [1], and port wine stain (PWS) skin (right) [2]. Bottom: PAM of traumatized skin [3].

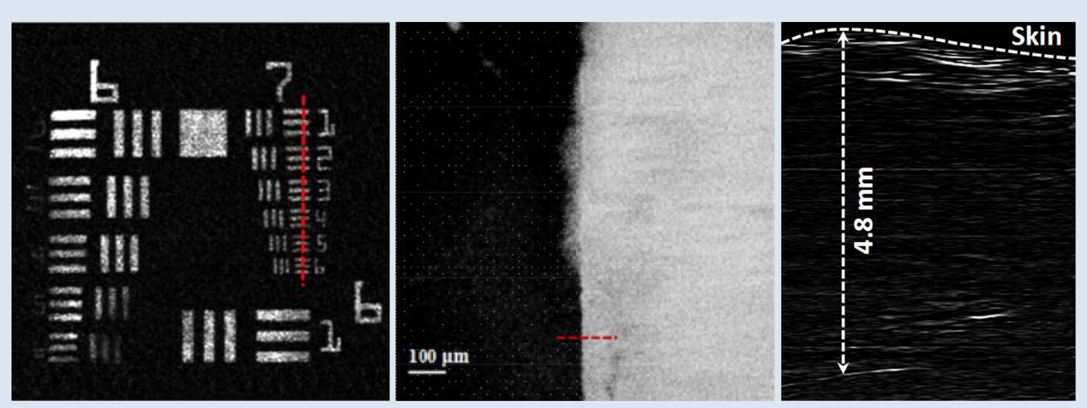


Figure 2. Illustration of commonly used test methods for PAM developers. Resolution: USAF target (left) [4], edge of a sharp blade (middle) [5]. Penetration depth: endogenous targets in in vivo animals [6].

Material Properties

- **Polyacrylamide (PAA) hydrogel with Tween 20 surfactant**
- **Nigrosin dye (absorption), TiO_2 nanopowder (scattering)**
- **Properties were tuned to match ranges from literature**

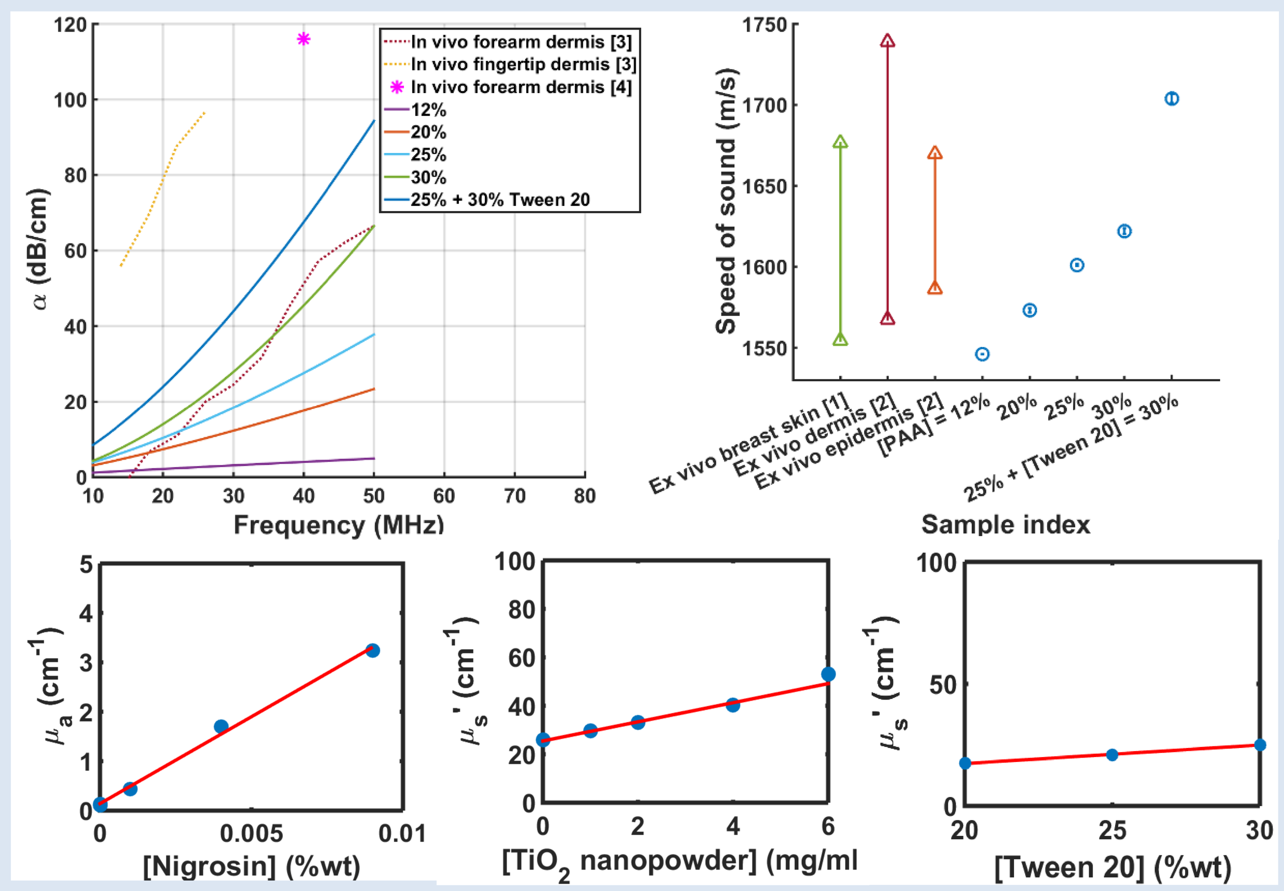
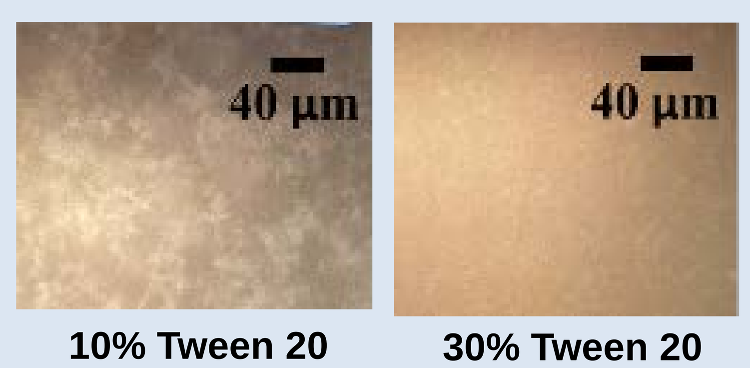


Figure 3. Acoustic (top), and optical (bottom) properties of PAA gel mixtures.



Properties:
- Acoustic
  - α: attenuation
  - c : speed of sound
- Optical
  - μ_a: absorption coefficient
  - μ_s': reduced scattering coefficient

Figure 4. Microscopy of PAA gels showed good dispersion of TiO_2 at 30% Tween 20(left) vs.10% (right).

Custom PAM System

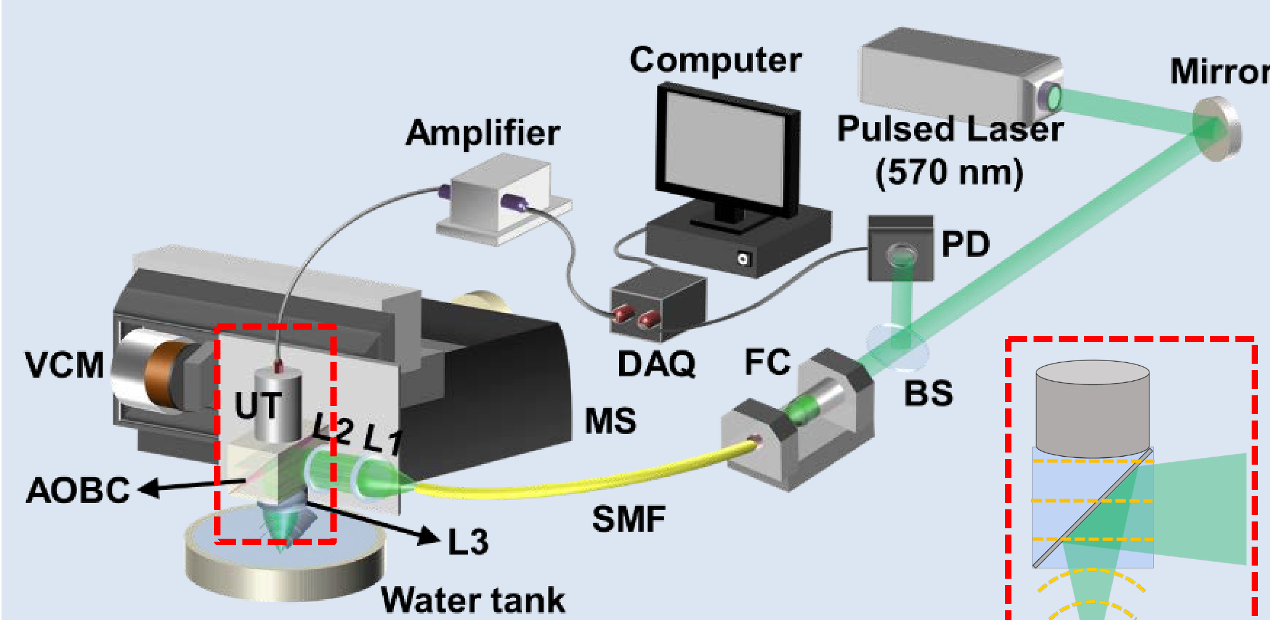


Figure 5. Schematic of the custom-built PAM system

- **PAM operated at 570 nm wavelength for vascular imaging**
- **Images were formed by raster-scanning**

Phantom Design

- **Phantoms made from three TMM recipes with low, medium, or high optical attenuation within the reported range**
- **Phantom 1: resolution phantom [7]**

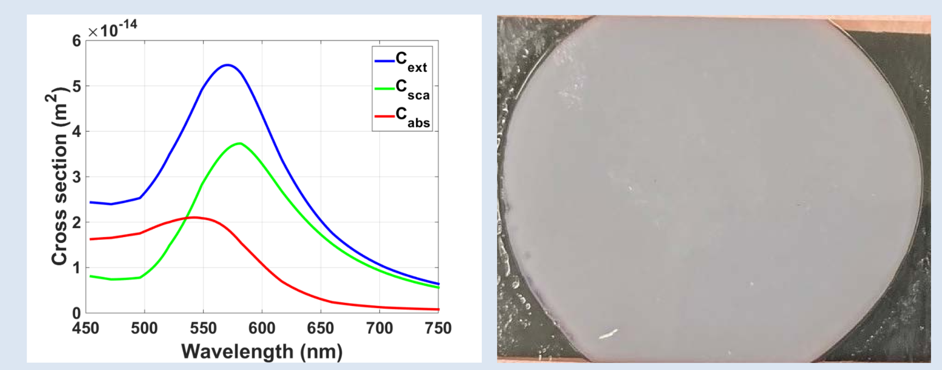


Figure 6. Sub-resolution (100-nm) gold nanosphere optical properties (left). Disc-shaped resolution phantom (right).

- **Phantom 2: penetration phantom**
- **Slanted threaded tungsten filament and blood-filled tube as blood vessels**

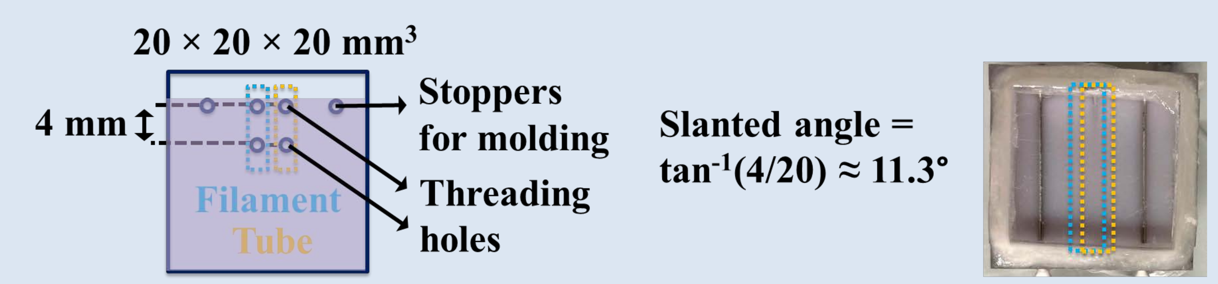


Figure 7. Schematic (left) and photo (right) of a penetration phantom with low TMM.

Resolution Testing

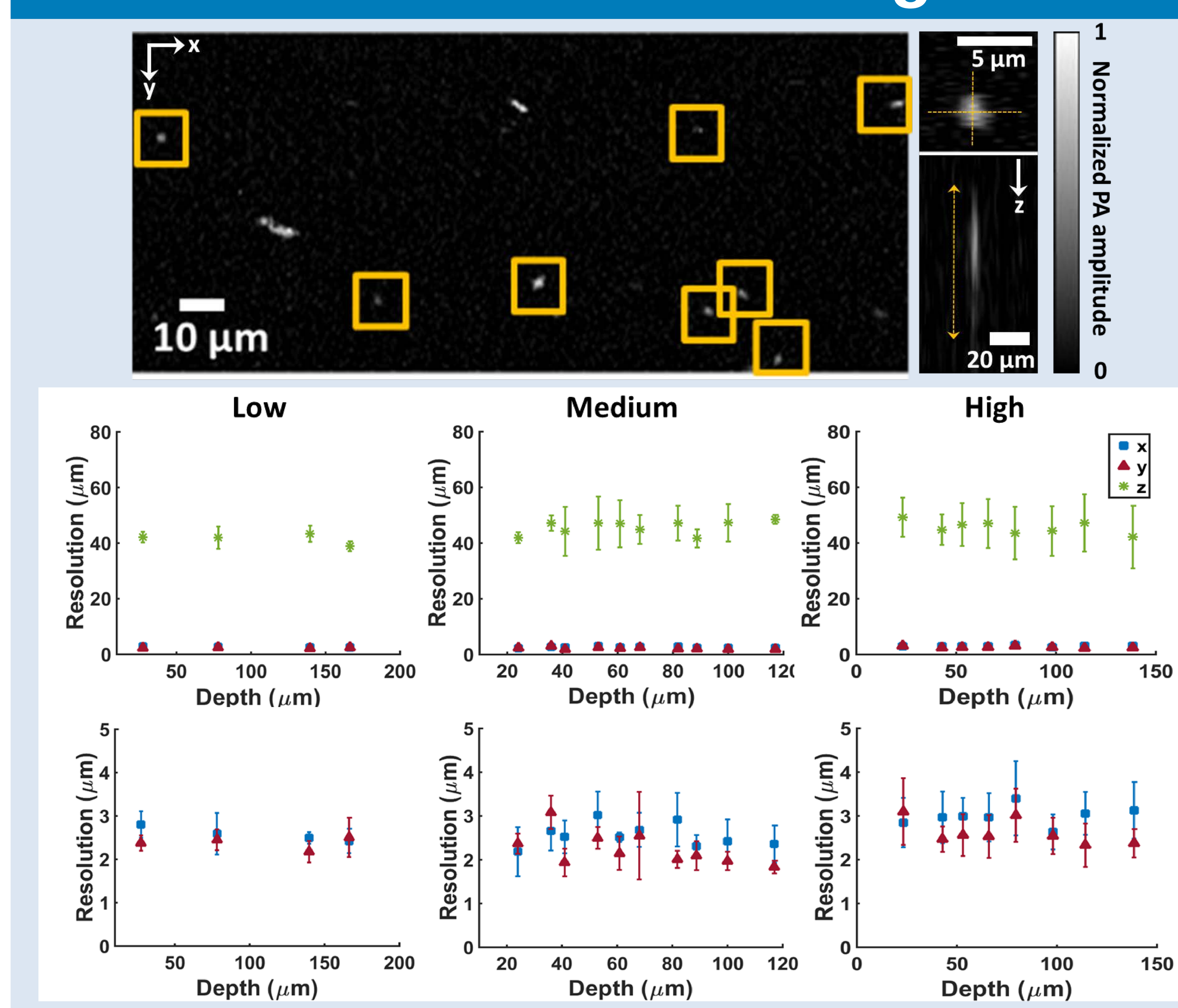


Figure 8. Top: illustration of PAM images of a resolution phantom with high TMM. Bottom: 3D spatial resolution measurements in phantoms with low, medium, and high optical attenuation.

- **Lateral resolution: ~ 2.5 µm; axial resolution: ~ 45 µm**
- **Spatial resolution degradation was insignificant within a depth range < 200 µm**

Imaging Depth Testing

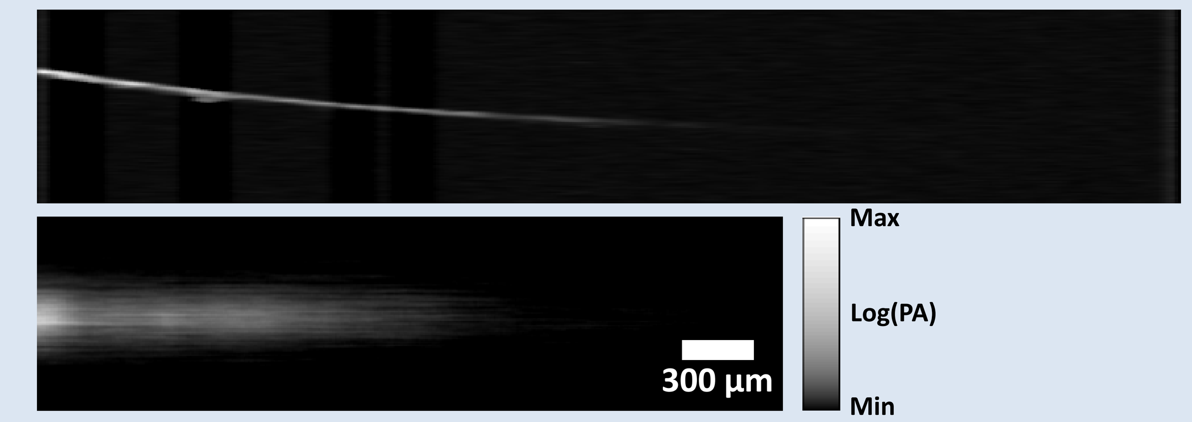


Figure 9. Representative PAM images of tungsten filament (top), and blood-filling tube (bottom) in penetration phantom with medium TMM.

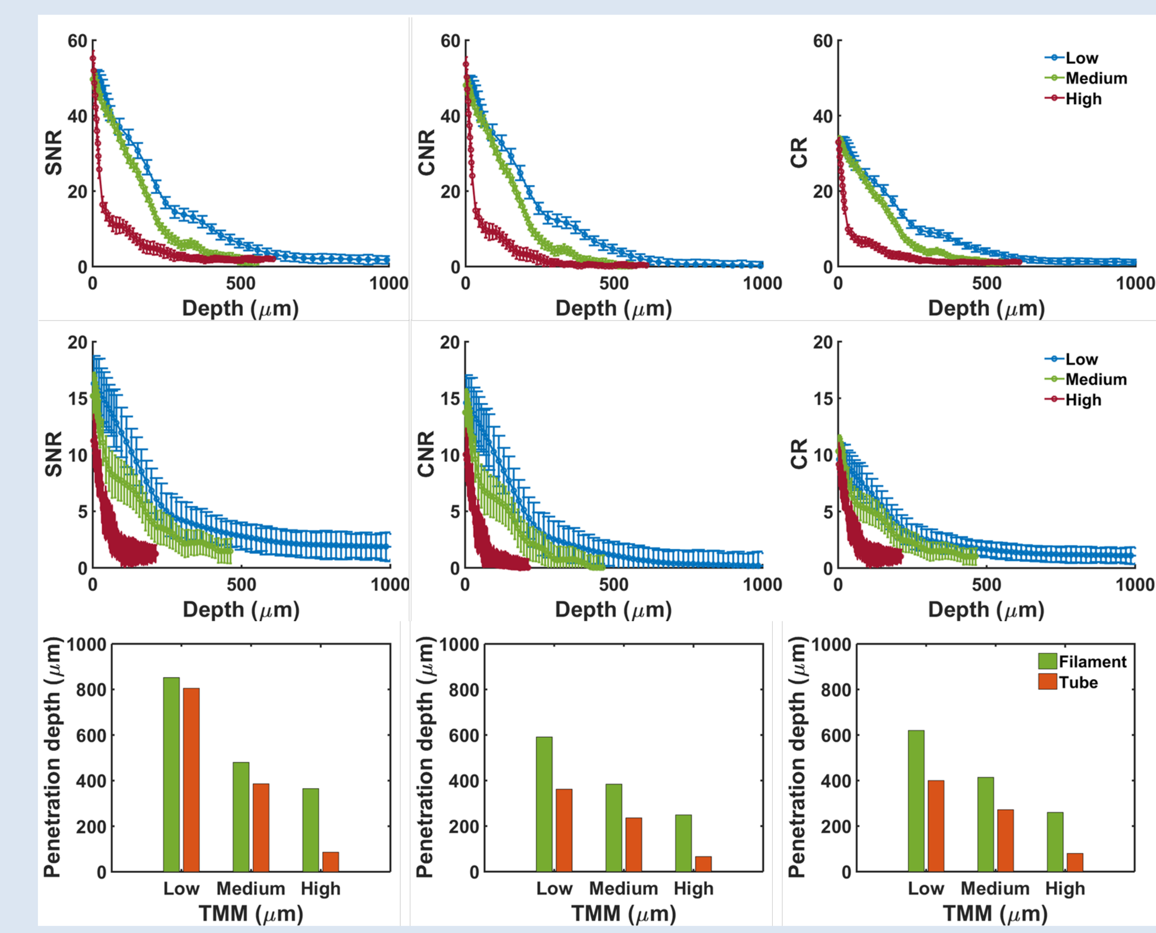


Figure 10. signal-noise ratio, contrast-noise ratio, and contrast ratio vs. depth (top and middle rows). Max imaging depth using 6 dB limit (bottom).

- **Higher variation for tubes due to weaker signal, averaging**
- **Filament overestimates imaging depth vs. tube**
- **Choice of image quality metric affected test results**

Conclusions

We developed a PAA-based human dermis TMM with tunable optical and acoustic properties and successfully demonstrated its use for performance evaluation of a custom-built PAM system. This work will advance establishment of standardized performance test methods to facilitate clinical translation of PAM medical devices.

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