

DATG 2.0 Integrated Liquid Crystal Sensing Platform and Tissue-Equivalent Phantom for High-Resolution Thermovascular Imaging

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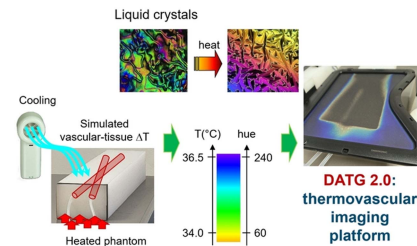
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Abstract—In this letter, we present the DATG 2.0 project, aimed at developing a portable, radiation-free sensor for the 3-D reconstruction of semisuperficial vascular structures (up to 4–6 cm depth). The system is based on the integration of flexible liquid crystal sensors, high-frame-rate RGB imaging, and a dedicated cooling module. Surface cooling induces the thermal transient required to detect deeper vessels. The resulting temporal sequence of RGB images can be then processed using algorithms based on the inversion of the Fourier heat conduction equation to extract depth information. To validate the proposed system, a dedicated experimental setup was developed, including tissue-equivalent phantoms made of platinum-cured silicone with homogenous heating and hot millimeter-scale channels, designed to assess spatial resolution and reconstruction performance; a test system combining an infrared camera for hue-to-temperature conversion and for characterization; and an optical bench with adjustable supports to ensure reproducibility. Preliminary results indicate that the system is capable of providing high-resolution images of semisuperficial vascular structures. The DATG 2.0 platform provides an experimental basis for future developments in thermovascular mapping, with potential applications in clinical practice and telemedicine.



Index Terms—Sensor applications, biosensors, flexible sensors, liquid-crystal sensors, medical imaging, thermal imaging.

I. INTRODUCTION

In recent years, infrared thermal imaging has regained attention as a noninvasive diagnostic tool thanks to advances in high-resolution sensor miniaturization and portability, together with the development of dedicated algorithms [1], [2]. These technological improvements have extended its potential clinical applications, including the monitoring of musculoskeletal and circulatory conditions, the analysis of acute metabolic stress in sports physiology, and the characterization of metabolic disorders through advanced data analysis approaches [3], [4]. In this context, thermochromic liquid crystals (TLCs) have emerged as a cost-effective infrared imaging technique, providing high spatial resolution and adjustable thermal sensitivity [5], [6], for example to monitoring wound healing processes. These studies indicate that the potential applications of TLCs may extend to other medical fields, including the assessment of musculoskeletal inflammatory conditions in sports medicine, the early detection of diabetic foot complications [7], and the real-time follow-up of pharmacological therapies [8].

In the current literature, tissue-mimicking phantoms have been widely developed to reproduce dielectric and electrical properties for microwave applications [9], [10], or to match the thermal properties of biological tissues, such as specific heat and thermal conductivity [11].

Some models include embedded resistive wires [11], [12] or agar-based matrices [14], [15] to simulate internal heat sources; however, they are often based on simplified geometries or rely on passive cooling systems [9], [16]. None of these studies proposes 3-D thermal phantoms dedicated to liquid crystal characterization and simulating complex vascular structures.

Despite its expanding diagnostic scope, contact thermography remains inherently 2-D, and the influence of surface cooling on image quality is still poorly characterized. Controlled thermal gradients are therefore required to suppress superficial vascular contributions and enhance deeper signals by promoting heat diffusion to the surface, which is essential for 3-D reconstruction approaches.

Dynamic AngioThermoGraphy (DATG) 2.0 project, funded within the DARE, digital lifelong prevention initiative, aims to overcome the limitations described above by advancing noninvasive screening toward a portable solution. DATG2.0 differs from conventional thermography because it is not designed to distinguish tissues or pathological abnormalities by measuring their temperature, but rather to employ controlled thermal transients to reconstruct the semisuperficial vascular pattern. More generally, the platform is conceived as a thermally driven imaging system rather than a temperature-monitoring tool, with potential extension to other anatomical targets exhibiting localized thermal contrast. The DATG 2.0 platform is a noninvasive, radiation-free sensing system designed for the 3-D reconstruction of semisuperficial vascular patterns (up to 4–6 cm depth). Advancing beyond previous work, the proposed system integrates novel flexible

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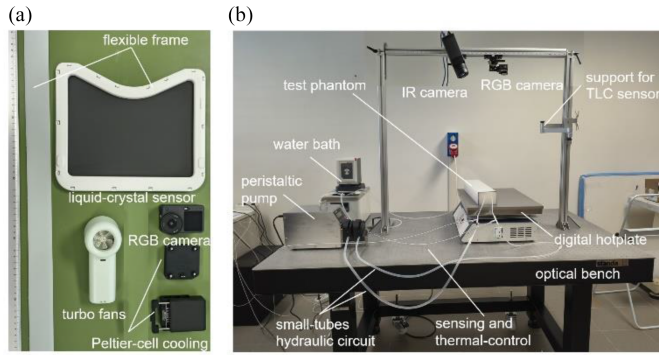


Fig. 1. DATG 2.0 platform. (a) Integrated sensing components. (b) Overall experimental setup.

liquid crystal detectors, active cooling, and custom thermal phantoms to acquire and elaborate high-resolution thermal transients. In this work, we present the first experimental results obtained with the newly developed system and the tissue-equivalent phantoms designed for preliminary validation. These findings provide an initial technical foundation for further refinement of the platform and for future applications in medical screening and telemedicine.

II. MATERIALS AND METHODS

A. DATG2.0 Sensor

The design of the DATG 2.0 platform (see Fig. 1) builds on previous studies that characterized liquid crystal sensors and demonstrated the feasibility of extracting depth-resolved vascular information from dynamic thermographic sequences through the inversion of the Fourier heat conduction equation [17], [18]. The core component is a TLC detector, engineered as an ultra-thin film (thickness $< 200 \mu\text{m}$) to reduce lateral thermal crosstalk and minimize measurement inertia. These sensors are calibrated to provide a chromatic response within narrow physiological temperature ranges (34°C – 36.5°C , 36.5°C – 38°C , and 38°C – 40°C), ensuring consistent diagnostic performance across patients with different baseline conditions. To achieve conformal coupling with complex anatomical geometries, the sensing layer was integrated into a custom 2 mm flexible frame made of a nontoxic, inert plastic material, providing the surface adaptability to nonplanar anatomical surfaces, and structural rigidity required to preserve TLC integrity.

The digital acquisition chain features a visible DJI Osmo Action six camera which integrates a 1/1.1-inch 38 MP square CMOS sensor providing a 13.5-stop dynamic range and a variable aperture ($f/2.0$ – $f/4.0$). This unit can record uncompressed RGB sequences at 120 frames per second, a temporal resolution critical for capturing the rapid thermal transients required by depth-inversion algorithms.

To provide quantitative temperature mapping, the RGB images are converted into hue, the physical parameter that serves as the primary scalar response, as demonstrated in [17]. Hue is monotonic within the activation range, and it is independent to illumination intensity. Although the full hue scale extends from 0 (red) to 360 (fuchsia), the DATG 2.0 sensors operate within a specific chromatic window: from yellow ($H \approx 60$) through green and cyan to blue ($H \approx 240$). This chromatic range was calibrated to match the target physiological windows associated with the healthy baseline temperature distribution of the population. Accordingly, the sensors are defined related to their thermal-threshold response: in the high thermal-threshold configuration, the 60–240 hue interval maps to 34°C – 36.5°C for

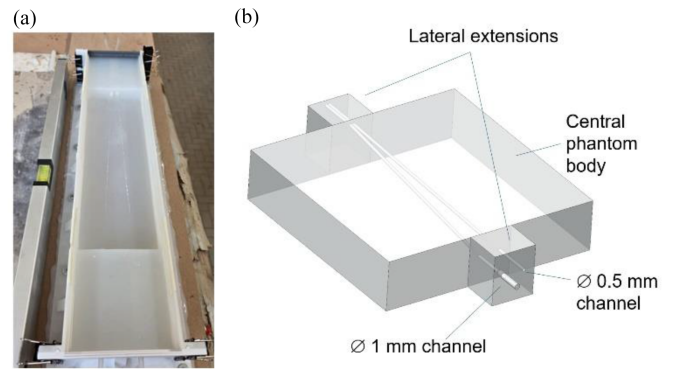


Fig. 2. (a) Photograph of the mold during casting, illustrating the suspended-wire technique to fabricate tubeless channels. (b) CAD design of the phantom for testing resolution at different depths.

the high-sensitivity sensor, to 36.5°C – 38°C for the mid-sensitivity sensor, and to 38°C – 40°C for the low-sensitivity sensor.

Finally, to optimize thermal contrast and suppress superficial noise, the platform includes a cooling system with two modalities: Peltier-effect modules and high-speed turbo fans operating at 13 500 r/min and 8.5 m/s airflow.

B. Thermal Phantom Design and Fabrication

The DATG2.0 phantom must replicate internal vascularization by simulating the physiological temperature gradient between blood vessels (38°C) and surrounding tissue (36°C), while exhibiting acoustic impedance and sound speed (target 1540 m/s) compatible with ultrasound scanner for direct thermographic-ultrasound comparison. Following a wide literature review [11], [19] and experimental tests, two platinum-cure silicones were selected for their bio-characteristics: Dragon Skin 10 NV and Ecoflex 00-30. Dragon Skin 10 NV provided structural stability for vascular conduits during casting, while Ecoflex 00-30 was chosen for its lower stiffness and greater compliance in simulating compressible tissues, such as the mammary gland.

The final phantoms will implement three geometric complexity levels sharing a common external structure ($30 \times 30 \times 7 \text{ cm}^3$ central block with $5 \times 5 \times 7 \text{ cm}^3$ lateral extensions for temperature stabilization), but differing in internal vascular layouts: one with single 1 mm channel at variable depths (0.5–4 cm) to assess vertical resolution; one with two Y-shaped 1 mm channels converging from 20 to 1 mm to determine in-plane limits and the last one with four overlapping/crossing channels at varying depths to study complex geometries. The silicone matrices were cast within dedicated molds, custom-manufactured, based on our original CAD designs [see Fig. 2(b)], and were produced via vacuum casting to ensure bubble free volumes. Experimental results confirmed that, in the absence of this methodology, the system loses acoustic transparency. An innovation of the project is the fabrication of tubeless vascular channels directly within the silicone matrix. The suspended-wire technique employs 1 mm-diameter wires under high tension across the mold prior to pouring [see Fig. 2(a)]; postcuring extraction yields hollow conduits matching wire dimensions. This eliminates insulating layers typical of tubed systems, which may alter heat diffusion, ensuring vessels are simulated solely by the fluid-silicone interface.

The hydraulic circuit is driven by a four-channel programmable peristaltic pump (flow rate 0.005–1495 mL/min). The temperature of the circulating fluids in vascular channels is independently set at $38^\circ\text{C} \pm 0.02^\circ\text{C}$ using a thermostatic water bath. Initial laboratory tests confirmed that peristaltic pump operation at low flow rates is essential for leak-proof integrity.

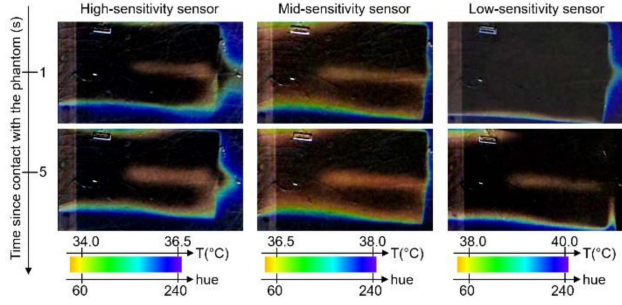


Fig. 3. RGB and hue responses at 1 s and 5 s after initial contact with the phantom.

C. Validation Setup

The experimental setup is based on an optical bench ($180 \times 90 \text{ cm}^2$) with a bridge-shaped stative and graduated joints, providing repeatable positioning and coregistration of the multimodal imaging chain including the liquid crystal sensor, and offering translational and rotational degrees of freedom.

The sensing platform integrates a FLIR A655sc infrared camera (640×480 pixels) to monitor surface temperatures at acquisition rates up to 200 Hz. For internal geometric validation and hemodynamic characterization, a portable Esaote MyLab C30 ultrasound system is employed, selected for its unique capability to export raw Doppler and microvascular profiles. A NI CompactDAQ system with 12 thermal sensors was programmed for automated control of phantom and fluid heating via pump, waterbath regulation, and real-time readout.

III. RESULTS AND DISCUSSION

A. Material Characterization

Ultrasonic characterization of the materials was performed using two experimental setups. The speed of sound was determined using a pair of 2 MHz piezoelectric transducers, one used as a transmitter, and the other as a receiver, driven by an ultrasonic wave generator and monitored with an oscilloscope. The acoustic impedance was calculated as $Z = \rho c$, where ρ is the material density and c is the measured speed of sound. Through-thickness ultrasonic transparency and echogenicity were evaluated using a clinical ultrasound scanner equipped with a 1–8 MHz convex-array probe. The measured sound speeds were $1044 \pm 15 \text{ m/s}$ for Dragon Skin and $1031 \pm 15 \text{ m/s}$ for Ecoflex. Both silicones exhibited an acoustic impedance of approximately 1.1 MRayl and remained ultrasonically transparent over propagation paths exceeding 10 cm. Their surface emissivity ranged from 0.95 to 0.98, as measured with the infrared camera, closely matching that of human skin (0.96–0.99). Rigid silicones, Smooth-Sil 950 and Mold Max 60, were discarded due to their nonphysiological mechanical response and nonacoustic transparency.

B. Experimental Tests

Preliminary tests were conducted on a first reduced-scale phantom ($30 \times 10 \times 7 \text{ cm}^3$) to assess the hydraulic and heating systems, as well as the integrity of the internal channels and the tube-channel interface. The phantom included 10 cm of embedded tubing on both sides (3 mm diameter) and a single internal 1 mm channel extending from 1 cm below the surface to 5 cm depth, while the tubing was positioned 1 cm below the surface.

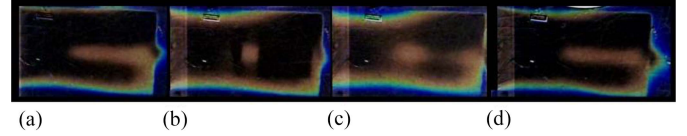


Fig. 4. TLC response for the high sensitivity sensors after 1 s under different cooling conditions, using the same chromatic scale as in Fig. 3. (a) No cooling. (b) 3 s Peltier cooling. (c) 4 s fan cooling with Peltier-assisted airflow. (d) 8 s fan-only cooling.

Table 1. Resolution of the Three Liquid Crystals Screens

Sensor's sensitivity	Conversion Factor (°C/hue)	MTF at 10% without cooling (lp/mm)	MTF at 10% with cooling (lp/mm)
High (34.0–36.5 °C)	0.014	0.15	0.27
Mid (36.5–38.0 °C)	0.008	0.20	0.31
Low (38.0–40.0 °C)	0.011	0.30	0.66

Achieving thermal uniformity was limited by silicone's low thermal conductivity. Reaching the 34 °C surface target required operating the hotplate and water bath at 90 °C, utilizing bubble-wrap, foam, and Plexiglas shielding. Despite these set-points, environmental dissipation resulted in a 39 °C inlet temperature and a 5 °C gradient across the phantom, successfully stabilizing the surface at ≈ 35 °C. These research-through-design trials identified the physical limits of biomimetic materials, informing future iterations, such as metal-encapsulated housings, for improved lateral heat distribution. Nonetheless, this setup enabled a robust assessment of cooling effectiveness and the response of the three liquid crystal sensors.

The high-sensitivity sensor saturated rapidly, whereas the medium-sensitivity sensor preserved the signal for a few seconds. The low-sensitivity sensor enabled slower, more controlled RGB formation and better tracking of the vascular thermal dynamics.

Active cooling was evaluated using a high-speed turbo fan, Peltier-effect modules, and their combination. The fan provided the most effective convective cooling, with 5–8 s pulses yielding a moderate surface temperature decrease and slow, controlled image formation [see Fig. 4(d)]. In contrast, the Peltier cell induced an abrupt thermal reduction: a 3 s pulse already drove the liquid crystals below their activation range [see Fig. 4(b)], while a 4 s combined pulse partially suppressed the sensor response and degraded image visibility [see Fig. 4(c)]. Overall, cooling was essential to suppress the superficial signal, as shown by the comparison between Fig. 4(a) and (d).

C. Response Analysis

The temperature increment per discrete hue unit (°C/hue) was determined within the 60–240 monotonic range, while spatial resolution was evaluated via the modulation transfer function (MTF) to provide a description of the system's resolving power across the spatial frequency spectrum, objectively quantifying the surface signal broadening induced by subsurface heat diffusion and the resulting efficacy of active cooling. For the analysis, RGB images were converted to grayscale, with a spatial sampling of 0.24 mm/pixel (measured at 50 cm distance). Results for the three sensors are summarized in Table 1 and MTFs are in Fig. 5. The low-sensitivity sensor demonstrated a spatial resolution of 0.66 lp/mm at 50 cm; at the 15-cm operational distance of the final handheld prototype, at least a fourfold improvement is expected.

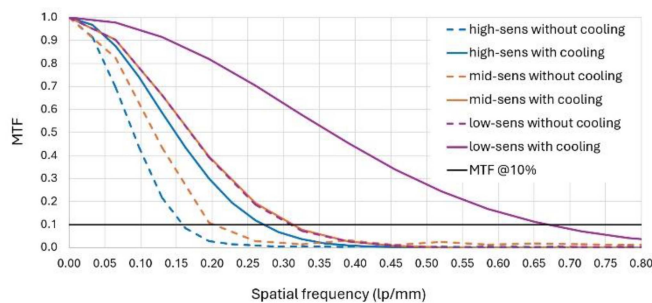


Fig. 5. MTF for the three sensors with and without cooling.

The image formation dynamics shown in Fig. 3 are physically governed by the interaction between the LC activation window and lateral heat diffusion within the silicone matrix. The sensors respond very rapidly within different thermal ranges, depending on their sensitivity. As shown in Fig. 4 and Table 1, active cooling improves image quality by suppressing superficial signals and establishing a steeper vertical gradient. As reported in [17] and [18], this mechanism enhances the detection of localized and deeper heat sources by driving a rapid heat-diffusion flux toward the sensing plane. This enables selective formation of the vascular pattern, here simulated as a single heated channel at fixed depth.

IV. CONCLUSION

This work establishes an experimental baseline for the DATG 2.0 liquid crystal sensor through validation of tissue-equivalent phantoms. Active surface cooling suppresses superficial signals and improves detection of deeper thermal sources. A reduced working distance in the final handheld prototype is expected to further improve spatial resolution. Future clinical studies will provide the data required for software development and for assessment of the system's diagnostic potential relative to clinical standard techniques.

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