RESEARCH ARTICLE

A three-dimensional strain measurement method in elastic transparent materials using tomographic particle image velocimetry

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Abstract

Background

The mechanical interaction between blood vessels and medical devices can induce strains in these vessels. Measuring and understanding these strains is necessary to identify the causes of vascular complications. This study develops a method to measure the three-dimensional (3D) distribution of strain using tomographic particle image velocimetry (Tomo-PIV) and compares the measurement accuracy with the gauge strain in tensile tests.

Methods and findings

The test system for measuring 3D strain distribution consists of two cameras, a laser, a universal testing machine, an acrylic chamber with a glycerol water solution for adjusting the refractive index with the silicone, and dumbbell-shaped specimens mixed with fluorescent tracer particles. 3D images of the particles were reconstructed from 2D images using a multiplicative algebraic reconstruction technique (MART) and motion tracking enhancement. Distributions of the 3D displacements were calculated using a digital volume correlation. To evaluate the accuracy of the measurement method in terms of particle density and interrogation voxel size, the gauge strain and one of the two cameras for Tomo-PIV were used as a video-extensometer in the tensile test. The results show that the optimal particle density and interrogation voxel size are 0.014 particles per pixel and 40 × 40 × 40 voxels with a 75% overlap. The maximum measurement error was maintained at less than 2.5% in the 4-mm-wide region of the specimen.

Conclusions

We successfully developed a method to experimentally measure 3D strain distribution in an elastic silicone material using Tomo-PIV and fluorescent particles. To the best of our
knowledge, this is the first report that applies Tomo-PIV to investigate 3D strain measurements in elastic materials with large deformation and validates the measurement accuracy.

Introduction

The mechanical interaction between blood vessels and medical devices can induce strains in these vessels. Measuring and understanding these strains is necessary to identify the causes of vascular complications [1–4]. Previous studies have relied on numerical structural analyses using the finite element method to evaluate the strain distribution in blood vessels [1–4]. However, the analysis conditions used were based on several assumptions that can significantly influence the results. This requires experimental validation [5–8]. Strain measurement techniques include strain gauging, digital image correlation, shearography, speckle interferometry, thermal stress analysis, and reflectometry. However, when using such techniques, the measured regions are limited to points or surfaces rather than three-dimensional (3D) regions inside the object [9]. This limitation implies that the results of numerical structural analyses are difficult to validate and highlights the challenges when measuring 3D strain distribution.

Digital volume correlation (DVC) allows for the generation of a 3D strain. In previous DVC studies, 3D images were obtained via X-ray computed tomography (CT) [9–13], magnetic resonance imaging (MRI) [14], and ultrasonic pulse-echo imaging [15, 16]. DVC has been used to measure strain in three dimensions in various materials, including bone [8, 9, 11–14] and skin tissues [15, 16]. However, measuring the strain in blood vessels using conventional DVC is impossible owing to the low time resolution of 3D imaging equipment such as CT, MRI, and ultrasonic pulse echo. When we target measurement of strain in blood vessels for example, the aorta has a typical inner diameter of 25 mm and a wall thickness of 2 mm that deforms at an average speed of 4.2 mm/s during a heartbeat.

Tomographic particle image velocimetry (Tomo-PIV) is used to measure the 3D flow velocity distribution at high spatial and time resolutions [17–23]. In Tomo-PIV, 2D images of flowing tracer particles in a fluid are captured using several cameras. The distribution of the displacements is then analyzed via a 3D reconstruction technique and DVC. In biomedical engineering applications, the flow velocity distribution is usually evaluated by tracking the flowing particle patterns in a transparent vessel model [22].

This study develops a method to measure 3D strain distributions using Tomo-PIV and compares the measurement accuracy of the strain between marked lines in tensile tests.

Materials and methods

Test specimen

The test specimens were made from transparent silicone (KE-1603, Shin-Etsu Chemical, Tokyo, Japan) mixed with fluorescent tracer particles with a mean diameter and density of 13 μm and 1.1 g/cm³, respectively (Fluostar, EBM, Tokyo, Japan). A planetary centrifugal mixer (AV-310, Thinky, Tokyo, Japan) was used to uniformly mix the particles and liquid silicone and deaerate the silicone. The liquid silicone was solidified via heating at 70˚C for over 1 h in sheet form with a thickness of 2.00 ± 0.01 mm corresponding to the aorta wall thickness (Fig 1a). A silicone sheet with an elastic modulus of 2.9 ± 0.1 MPa was prepared. Then, type-2 dumbbell-shaped specimens were punched out according to Japanese Industrial Standards (JIS K 6251) and the International Organization for Standardization (ISO 37:2011). Two gauge lines were marked at 20-mm intervals along the parallel portion of the specimens (Fig 1a).
Specimens with particle densities of 0.008, 0.014, 0.020, and 0.026 particles per pixel (ppp) were manufactured for this Tomo-PIV system to evaluate the influence of particle density on measurement accuracy.

**Experimental setup**

The experimental setup consisted of two 12-bit complementary metal oxide semiconductor (CMOS) cameras with a full resolution of 2016 × 2016 pixels (Imager pro HS 4M, Lavision, Gottingen, Germany), a neodymium-doped yttrium lithium fluoride (Nd:YLF) laser (DS20-527, Photonics Industries, NY, USA), a universal testing machine (AG-X, Shimazu, Kyoto, Japan), an acrylic chamber, and a silicone specimen (Fig 1c, 1d and 1e). The experimental parameters are given in Table 1. Tensile tests were performed for the four specimens with different particle densities at a tensile speed of 50 mm/min [24, 25]. A 6-mm-thick laser sheet obtained using a beam expander and a series of optical lenses was irradiated at the center of

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*Fig 1. Schematic of the experimental system for measuring strain using Tomo-PIV. (a) Silicone specimen. (b) Schematic drawing of the area of strain measurement. (c) Top view of the experimental system. (d) Front view of the experimental system. (e) Experimental system.*

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the specimens (Fig 1b). The measurement region was 4 mm × 10 mm × 2 mm above the line of the lower gauge (Fig 1b). The cameras were angled at 45˚ along the direction of the laser sheet (Fig 1c). The camera lenses (Micro NIKKOR 85 mm, Nikon, Tokyo, Japan) had a focal distance of 85 mm and a lens aperture of f = 20. The cameras were focused on an area of approximately 45 mm × 45 mm, which corresponds to a magnification of M = 0.49. An aberration correction for the lens was performed using a calibration target (type 058–8, Lavision, Gottingen, Germany). Three iterative self-calibration corrections were used to reduce the calibration error to less than 0.3 pixels [23]. An acrylic chamber equipped with two viewing prisms was constructed to enable the orthogonal views of each camera. The acrylic chamber was filled with a glycerol water solution. The refractive index of the glycerol water solution was adjusted to that of the test specimen, 1.417 ± 0.002, to avoid refraction. To maintain the uniformity of the temperature and refractive index of the glycerol water solution, the solution was continuously mixed and maintained at 25˚C using a thermal magnetic stirrer (MH301, Yamato Scientific, Tokyo, Japan).

Measurement of displacement and strain

The distribution of the normal strain in the tensile direction was calculated when the gauge strain was 10% using the following method. During the tensile test, 42 successive 2D images of the particles for each specimen were captured by the two cameras at a sampling rate of 10 Hz (Fig 2a), resulting in an acceptable average interframe particle displacement of 2–4 pixels in the measurement region [19, 22, 26]. The 3D images of the particles, with a discretization of 22 μm/voxel, were reconstructed from the 2D images using a multiplicative algebraic reconstruction technique (MART) [27] and motion tracking enhancement (MTE) with the number of objects set to N_o = 7 [18, 19] (Fig 2b). Ten iterations of the MART and MTE were conducted to improve the reconstruction accuracy [17, 18]. Each reconstructed 3D image was divided into cubic interrogation voxels (Fig 2c). Both the 3D reconstruction and the DVC were conducted using Davis 8.2.2 software (Lavision, Gottingen, Germany). The displacements of the

Table 1. Experimental parameters for strain measurements.

| Specimen | Material | Silicone (Refraction index n = 1.417) |
|----------|----------|--------------------------------------|
| Particle | Fluorescent particle (Diameter: 13 μm, Density: 1.1 g/cm³) |
| Particle density | 0.008, 0.014, 0.020, 0.026 ppp |
| Shape | Type-2 dumbbell shaped specimen (JIS K 6251, ISO 37:2011) |
| Elastic modulus | 2.9±0.1 MPa |

| Laser | Device | Nd:YLF laser |
|-------|-------|--------------|
| Thickness | 6.0 mm |

| Camera | Resolution | 2016×2016 pixel |
|-------|------------|-----------------|
| Sampling rate | 10 Hz |

| Image properties | Lens focal length | 85 mm |
|------------------|------------------|-------|
| Lens aperture | f = 20 |
| Field of view | 45×45 mm |
| Image magnification | 0.49 |
| Viewing angle | ±° |

| 3D reconstruction | Method | MART (10 iterations), MTE (10 iterations) |
|------------------|-------|----------------------------------------|
| Resolution | 22 μm/voxel |

| Digital volume correlation | Method | Iterative multi-grid volume deformation scheme |
|---------------------------|-------|-----------------------------------------------|
| interrogation voxel size | 32×32×32, 40×40×40, 48×48×48, 56×56×56, 64×64×64 voxel |
| Overlap | 75% |

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Center points of each interrogation voxel were calculated from two successive 3D images via a commonly used fast Fourier transform-based cross-correlation algorithm using an iterative multi-grid volume deformation scheme with a Gaussian-weighted volume \[17, 20\] (Fig 2c).

The centers of each interrogation voxel at the starting point of the tensile test were defined as

\[d = \frac{\sum_{i=1}^{8} d_i \times w_i}{\sum_{i=1}^{8} w_i}\]

where \(d\) is inversely proportional to distance between any selected point and the center of an adjacent interrogation voxel.

(c) Displacement measurement

(d) Interpolation of displacement

(e) Sum of displacement

(f) Strain calculation

Fig 2. Procedure of 3D strain analysis in specimens incorporating fluorescent particles using Tomo-PIV.

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the inspection points. The displacement at any selected point was interpolated using eight
adjacent displacements according to the following equation (Fig 2d):

\[
d = \frac{\sum_{i=1}^{8} d_i \times w_i}{\sum_{i=1}^{8} w_i},
\]

Here, \(d\) is the displacement at each point and \(w\) is a weighting coefficient, which is inversely
proportional to the distance between an inspection point and the center of an adjacent interro-
gation voxel. The displacements of each inspection point before and after the tensile test were
estimated from the sum of their successive interpolated displacements during the tensile test
(Fig 2e). The normal strain in the specimen in the tensile direction was calculated using the
displacements of the inspection points before and after the tensile test according to the follow-
ing equation (Fig 2f):

\[
\varepsilon_{yy}(X, Y + \frac{l}{2}, Z) = \frac{d_y(X, Y + \frac{l}{2}, Z) - d_y(X, Y, Z)}{l}
\]

Here, \(l\) is the distance between the centers of two adjacent interrogation voxels and \(d\) is the
displacement at each inspection point. Both the interpolated displacements and the distribu-
tion of the normal strain were computed in MATLAB (MathWorks, Massachusetts, USA).

**Influence of particle density and interrogation voxel size on measurement accuracy**

The particle density and interrogation voxel size both influence the measurement accuracy. A
high particle density in the measurement region allows for a higher spatial resolution. How-
ever, spurious particles (ghost particles), which lead to measurement errors, are generated at
high particle density because the lines of sight to multiple particles intersect from several pro-
jections [20, 21]. Conversely, the number of particles in an interrogation voxel needs to be
greater than at least 5–10 to perform a robust Tomo-PIV [9, 10, 17]. Interrogation voxel sizes
of 24 × 24 × 24–64 × 64 × 64 voxels with a 50–75% overlap are typically adopted in Tomo-PIV
to realize high spatial resolution with small interrogation voxel size and a sufficient number of
particles in each interrogation voxel [17, 19, 22, 26]. Overlap indicates the overlap between
neighboring interrogation voxels and is broadly used to measure local flow velocities [19, 22,
26]. The distance between the centers of two adjacent interrogation voxels was calculated
according to the following equation:

\[
\text{Distance between the centers of two adjacent interrogation voxels} = \text{interrogation voxel size} \times \frac{100 - \text{overlap ratio}}{100} \times \text{voxel discretization}.
\]

In this study, a 75% overlap was adopted in all tests to measure the local strain distribution.

**1 Influence of particle density.** In terms of eliminating the measurement error due to
the generation of ghost particles, the optimal particle density was investigated in a sufficiently
large interrogation voxel size of 64 × 64 × 64 voxels. With reference to the reconstruction qual-
ity factor Q of Tomo-PIV using two cameras in a previous study [20], specimens with particle
densities of 0.008, 0.014, 0.020, and 0.026 ppp were prepared. The average numbers of particles
in the interrogation voxels in each specimen were 45, 91, 152, and 257, respectively, showing
that the four specimens with different particle densities had sufficient numbers of particles to
perform a robust Tomo-PIV.
(2) Influence of interrogation voxel size. To investigate the optimal interrogation voxel size in terms of having better spatial resolution, the normal strain distributions were compared between interrogation voxel sizes of $32 \times 32 \times 32$, $40 \times 40 \times 40$, $48 \times 48 \times 48$, $56 \times 56 \times 56$, and $64 \times 64 \times 64$ voxels. The optimal density found in the previous experiment was used. A 75% overlap was applied for the measurement. The distances between the centers of two adjacent interrogation voxels for interrogation voxel sizes of $32 \times 32 \times 32$, $40 \times 40 \times 40$, $48 \times 48 \times 48$, $56 \times 56 \times 56$, and $64 \times 64 \times 64$ voxels with a 75% overlap were 8, 10, 12, 14, and 16 voxels, respectively. The numbers of interrogation voxels used in the analyses were 14674, 7513, 4347, 2738, and 1834 voxels, respectively.

(3) Assessment of measurement conditions. The appropriate particle density and interrogation voxel size were examined in terms of measurement error, which was defined as the difference between the strain measured by Tomo-PIV and the gauge strain measured using binary images captured with one of the cameras of Tomo-PIV. The correlation value between two successive 3D images was used as an accuracy indicator of the displacement measurements under all conditions [10].

(4) Statistical analysis. In this study, a statistical analysis was performed using a software package (SPSS Statistics version21, IBM, NY, USA). For continuous variables, the distribution of normality and the equality of variances were assessed according to the Shapiro–Wilk and Levene tests, respectively [28, 29]. Tukey’s test was performed to provide multiple comparisons for the equality of normally distributed variables [29]. A P value lower than 0.05 was considered statistically significant.

Results

Influence of particle density

The distributions of the correlation values and the normal strains in specimens with particle densities of 0.008, 0.014, 0.020, and 0.026 ppp at the cross section $Z = 0$ mm are shown in Fig 3a. The correlation value between the first two successive 3D images was higher than 0.94 over the entire measurement region of all the specimens (Fig 3a). The correlation values between other two successive 3D images showed equivalently high correlation values as that between the first two successive 3D images. The normal strains at the cross section $Z = 0$ mm were within $10 \pm 2\%$ for all the specimens. The mean correlation values for specimens with particle densities of 0.008 and 0.014 ppp were comparable, and those of 0.020 and 0.026 ppp decreased as particle density increased (Fig 3b). For all conditions, the mean normal strains were within $10 \pm 0.1\%$ (Fig 3c). The measurement errors of specimens with particle densities of 0.008 and 0.014 ppp were comparable and significantly smaller than those with particle densities of 0.020 and 0.026 ppp (Fig 3d). Based on these findings, the particle density of 0.014 ppp was selected in terms of its better measurement accuracy and spatial resolution.

Influence of interrogation voxel size

The mean correlation values between the first two successive 3D images decreased as the interrogation voxel size decreased (Fig 4a and 4b). The mean correlation values between other two successive 3D images also decreased as the interrogation voxel size decreased. The normal strain measured with an interrogation voxel size of $32 \times 32 \times 32$ voxels was locally higher than 13% (Fig 4a). The mean normal strains were $10 \pm 0.1\%$ for all interrogation voxel sizes (Fig 4c). The measurement error of the normal strain in an interrogation voxel size of $32 \times 32 \times 32$ voxels was significantly higher than those in other interrogation voxel sizes (Fig 4d). The measurement errors were comparable for interrogation voxel sizes of $40 \times 40 \times 40$, $48 \times 48 \times 48$, $56 \times 56 \times 56$, and $64 \times 64 \times 64$ voxels (Fig 4d). Based on these data, the interrogation voxel size...
Fig 3. Influence of the particle density of specimens on 3D strain measurement using Tomo-PIV with interrogation voxel sizes of $64 \times 64 \times 64$ voxels for the specimens. Specimens with particle densities of 0.008, 0.014, 0.020, and 0.026 ppp were compared at the cross section $Z = 0$ mm. (a) Distributions of the correlation values between the first two successive 3D images and the normal strain. (b) Correlation value between the first two successive 3D images. (c) Normal strain. (d) Measurement error of the normal strain.

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of 40 × 40 × 40 voxels was considered optimal in terms of its better measurement accuracy and spatial resolution.

The distributions of the correlation values between the first two successive 3D images and the normal strain in the cross sections of Z = 0, 0.8, 1.6, and 2.4 mm are shown in Fig 5a. The
The mean normal strains were 10 ± 0.1% at all cross sections (Fig 5c). The mean correlation value decreased and the maximum measurement error increased as the absolute value of Z increased owing to the low laser intensity at both surface layers of the 6-mm-thick laser sheet (Fig 5b and 5d). The maximum and minimum measurement errors of the normal strain in the measurement region between Z = −2 mm and Z = 2 mm were 2.5% and 1.1%, respectively.

**Discussion**

In this study, we developed a method to experimentally measure strain distributions in elastic silicone materials using Tomo-PIV and fluorescent particles. The accuracy of the
measurement method was evaluated in comparison to the gauge strain in the tensile test. The
results show that the optimal particle density and interrogation window size in terms of the
measurement accuracy and spatial resolution were 0.014 ppp and 40 × 40 × 40 voxels with a
75% overlap. Using this method, the distributions of the normal strain in elastic materials
when the gauge strain was 10% were successfully quantified, and the mean normal strain in
the specimen at the cross section Z = 0 mm was 10 ± 0.1%. The maximum measurement error
of the normal strain was less than 2.5% in the measurement region in a 4-mm-wide region of
the specimen. To the best of our knowledge, this is the first report that applies Tomo-PIV to
investigate 3D strain measurements in elastic materials with large deformation and evaluates
the measurement accuracy.

All previous studies using Tomo-PIV focused on flow investigations. Studies using DVC
have shown that the measurement error of the displacement is between 0.01 and 0.1 voxels
[10, 12, 24–28]. In the case where an interrogation size of 40 × 40 × 40 voxels with a 75% over-
lap was used in the measurement of the strain, the distance between the centers of two adjacent
interrogation voxels in the tensile direction was 10 voxels. The displacements of the adjacent
inspection points measured by the Tomo-PIV system included a measurement error between
0.01 and 0.1 voxels in each calculation using sequential 3D images. Therefore, the maximum
measurement error in the distance between two adjacent inspection points was between 0.02
and 0.2 voxels, leading to a measurement error of the normal strain between 0.2% and 2%. In
this study, the maximum measurement error of the normal strain was maintained at less than
2.5% in the 4-mm-wide region of the specimen even though the strain distribution was calcu-
lated from the sum of 41 successive interpolated displacements. These data indicate that the
measurement system using Tomo-PIV presented here would be feasible for investigating 3D
strain distributions in elastic materials with large deformation.

The accuracy of the strain measurement methodology presented here may be improved in
the following way. In this study, we used two cameras in Tomo-PIV for the measurement of
strain induced in the specimens, because the thickness of the specimens was 2 mm only. The
measurement accuracy obtained in this study was satisfactory. However, the measurement
using Tomo-PIV with two cameras has the limitations in the achievable seeding density. This
can be overcome if three or more cameras are used in the imaging system. When a thicker
specimen is tested, use of three or more cameras will contribute to the reduction of the inter-
section of lines of sight, and improvement of the measurement accuracy [17–23]. In an unde-
formed specimen, more accurate 3D reconstructions can be realized by acquiring images of
the specimen from three or more different viewing directions using a single camera. In this
study, the number of ghost particles was not measured because the optimal particle density
could be determined based on measurement errors without counting the ghost particles. How-
ever, the accurate 3D distribution of particles in an undeformed specimen can be used to esti-
mate the number of generated ghost particles for assessing the cause of the measurement
error. Note that the evaluation of the 3D strain measurement was limited because the 3D strain
was evaluated in comparison to the gauge strain, which is the average strain on the surface of
the specimens. Nevertheless, a highly homogeneous strain was likely loaded in the specimen
because the specimen was made from a single material with a uniform thickness of 2.00 ± 0.01
mm. Although, in this study, the displacements of the center points of each interrogation voxel
were calculated from two successive 3D images via a commonly used fast Fourier transform-
based cross-correlation algorithm [17, 20], application of direct correlation algorithm may fur-
ther improve accuracy of the measurement presented here [30].

The method presented here will be useful to experimentally measure the 3D distribution of
strain in elastic materials with large deformation. Accompanying the recent advancements in
3D modeling technology, the mechanical strain generated in cardiovascular tissues under external loads such as those caused by contact with medical devices can be quantified.

Conclusions
We applied a novel method to measure the 3D strain yielded in an elastic silicone material using Tomo-PIV and fluorescent particles. In this study, the optimal particle density and interrogation voxel size were determined in terms of the measurement accuracy and spatial resolution. Distributions of the normal strain in elastic materials were successfully quantified. This study showed that the method presented here is feasible to accurately measure 3D strain distributions. The method may also be useful to understand strain distributions that occur in tissues such as blood vessels that are in contact with implantable medical devices.

Author Contributions
Conceptualization: Azuma Takahashi, Kiyotaka Iwasaki.
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