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Measurement of current–voltage characteristics of curved photovoltaic modules for vehicle integration

Takeshi Tayagaki [*], Kengo Yamagoe, Munefumi Komori, Masahiro Yoshita

National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki, 305-8568, Japan

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A B S T R A C T

Curved surfaces look smart for automotive customers, however, are not easily accommodated by conventional flat photovoltaic (PV) panel technology. One of the major challenges for curved PV technology is to develop a consensus method for measuring the current–voltage characteristics of curved PV modules. In this study, we first investigated the current–voltage characteristics of a flexible crystalline silicon (c-Si) solar cell on a curved stage and modeled the effect of the solar cell curvature on the current characteristic. Then, we characterized the irradiance distribution of a solar simulator for a large PV module with an illumination area of 200 × 140 cm^2, including spatial light intensity and incident light angle distributions. Based on these results, we demonstrated that the measured current–voltage curve of a curved c-Si PV module with a size of ~120 × 70 cm^2 and a curvature radius of 1000 mm matched the calculated current–voltage curves considering the irradiation characteristics of the solar simulator and the current–voltage curve of a flat PV module. The requirements for the solar simulator used to measure the current–voltage characteristics of a curved PV module are discussed.

1. Introduction

Lightweight photovoltaic (PV) modules are essential for next-generation vehicle-integrated photovoltaic (VIPV) applications such as solar-powered cars, where solar cells can be integrated not only on the roof but also on the hood, trunk, and body panels to extend driving range [1]. Designing curved shapes is a key challenge for VIPV and module integration on curved surfaces has been addressed [2]. Curved surfaces look smart to automotive customers, however, which is not easily handled by conventional flat PV panels. Reflecting the large number of types of flexible solar cells [3] available for curved PV module applications, curved PV modules are increasingly integrated into a wide range of applications, including modern energy-efficient buildings [4], wearable devices [5], and agricultural greenhouses [6], in addition to vehicles [7]. The curvature of a curved surface varies greatly depending on the shape of the curve and the application of the curved PV modules [8]. Curved PVs that is not affected by orientation and has improved energy collecting efficiency have been proposed [9]. One of the characteristics of curved PV modules is that solar cells oriented in different directions must be considered. As a result, the current generation in the module is not uniform even with uniform light illumination. For modules consisting of a large number of solar cells, solar cells with different currents are connected, resulting in a current mismatch between the solar cells. In other words, the power depends on how the solar cells are connected [10]. Then, the solar cell interconnection is important module design factor in curved PV modules [11]. Moreover, the curved shape itself may cause self-shading and reduce solar irradiation on the panels [7].

Although the performances of flexible PV modules can be measured on flat surfaces, once fixed to a curved surface the output power can change due to non-uniform illumination on the curved surface. This can lead to fluctuations in the measured power of curved PV modules. The problem is that the conventional international standard IEC 60904 is based on a two-dimensional plan, which is also required for curved solar panels [12]. Regarding these challenges, IEC 60904-1, which specifies the measurement of photovoltaic current-voltage characteristics, states that the active surface of the device under test shall be coplanar within ±2°, and the reference device shall be placed in the test plane so that its active surface is coplanar within ±5° [13]. Furthermore, the standard state that the effect of spatial non-uniformity of irradiance shall be evaluated. However, there is no mention of curved active surfaces tilted by more than 2° and curved active surfaces with height and depth.

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* Corresponding author.
E-mail address: tayagaki-t@aist.go.jp (T. Tayagaki).

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Therefore, the current standard does not specify how to measure curved active surfaces.

In order to reduce the variation in the measured power of curved PV modules, the requirements of solar simulators is discussed for the consensus characterization of curved PV modules. For example, a collimated solar simulator has been studied and an ideal cosine response of the curvature has been shown [14]. Meanwhile, this solar simulator is limited to use in a test laboratory and not easily useable in a manufacturing site. Furthermore, the scientific aspects behind the standardization are stated in Ref. [15], including performance testing curved PV modules with reproducible measurements and energy rating. Additionally, power ratings are also required for module durability testing. If the product is repeatedly folded [16], it may be possible to evaluate it in a flat state, but if the product is fixed in a curved states, measurements on the curved surface are required for durability testing that is measuring performance before and after stress tests.

For energy rating, curved surface insolation has been investigated. Building-integrated photovoltaics (BIPVs) and VIPV receive solar irradiance through non-uniform shading objects [17]. The annual irradiance absorbed by a curved roof has been calculated [18]. To model the energy generation of a car roof PV system, the incidence angle distribution model of sunlight that considers direct and diffuse components is required [19]. In more practical conditions, solar irradiance includes not only direct beam but also diffuse irradiance. Diffuse horizontal irradiance is less affected by the angle of the solar panel due to its isotropic angle distribution, which can reduce the current mismatch between the solar cells and improve the energy yield of curved PV modules [20]. Since partial shading due to self-shading may depend on the outdoor conditions, device optimization can be achieved by carefully selecting the location to install the curved PV modules. Measurement and modeling of three-dimensional solar irradiance for VIPV have been demonstrated [21].

In this study, we measured the current–voltage curves of a flexible crystalline silicon (c-Si) solar cells with an area of 156 × 156 mm^2 on flat and curved stages to study the effect of curvature on the current and voltage of the solar cell. In addition, we characterized the irradiance distribution, such as the spatial light intensity and incident light angle distributions, of a solar simulator with an illumination area of 200 × 140 cm^2 for a large PV module. Based on these results, we compared the current–voltage curves measured on a curved PV modules with a size of ~120 × 70 cm^2 and a curvature radius of 1000 mm with the curves calculated considering the curve of a flat PV module and the irradiation characteristics of the solar simulator. The requirements for the solar simulator used for the current–voltage curve measurements of a curved PV module are discussed.

2. Experimental

Flexible c-Si solar cells [22] were used for solar cell characterization. Commercially available 156 × 156 mm^2 c-Si solar cells — specifically multi-crystalline Al back surface field (Al-BSF) structured solar cells were used. A customized solar simulator (WXS-220S-20) with AM1.5G irradiation spectra and highly collimated beam was used for current–voltage curve measurements, 90 % of the incident light was within the incident angle of 1.6°. The effective irradiated area was 220 × 220 mm^2. The non-uniformity of the illumination intensity was less than ±2 %, as revealed by intensity mapping measurements with 5 × 5 mm^2 resolution.

The flat and curve PV modules with a size of 1315 × 675 mm^2 are used for curved PV module measurements. The module consists of 8 × 4 arrays of 6-inch size solar cells. A customized solar simulator (WPSS-2.0 × 1.4–50 × 6) with AM 1.5G irradiation spectra was used for current–voltage curve measurements. The illumination area was ~2000 × 1400 mm^2.

3. Results and discussion

3.1. Measurements of curved solar cells

First, we investigated the effect of curved surfaces on the performance of solar cells, which are components of PV modules consisting of series-connected solar cells. Fig. 1 (a) shows a schematic of flexible c-Si solar cells placed on curved surfaces with curvature radii (R_c) of 0.5 m and 0.2 m. For car roof applications, the curve is gentle and the curvature radius is ~1 m or more depending on the position. Fig. 1(b) shows the current-voltage curves of flexible c-Si solar cells on curved stages with different curvature radii. The inset represents the enlargement near the short-circuit condition. Fig. 1 (c) shows the short-circuit current of a flexible c-Si solar cell as a function of the stage curvature. Fig. 1(d) shows a schematic of a curved solar cell. When light is incident vertically, the projected area of the curved surface, denoted by the reference flat area (A_{ref}), is smaller, compared to the curved surface area (A_{curved}), resulting in a decrease in photocurrent. The edges are tilted at 8.9° and 22.3°, respectively, which resembles a car roof type PV module with a curvature radius of 1 m or 3 m, as described later. The calculation considering the projected area correction is shown by the red curve in Fig. 1(c) and explains the experiment well. The results also show that the amount of photocurrent generated on a gently curved surface is comparable to that on a flat surface. These results indicate that the effect of cell curvature on power generation is negligible in practical modules, except for rolled solar cells with a curvature radius of 0.2 m or less.

3.2. Irradiance distribution of module solar simulator

Next, we characterized the irradiance distribution, including the spatial light intensity and incident light angle distributions, of a solar simulator with an illumination area of 200 × 140 cm^2 for large PV modules. Fig. 2 (a) shows a schematic of the illumination plane. The irradiance and incident light angle distribution were measured at the in-plane positions (x, y) marked with red circles. Fig. 2(b) shows the relative irradiance as a function of the relative position in the front-to-back direction of the illumination plane. It was confirmed that the spatial distribution of illumination intensity in front of and behind the reference plane follows the inverse square law of distance. The change in the relative position of the illumination surface is 0.3 %/cm. This means that the volume non-uniformity is 1.5 % when measuring a module with a height of 10 cm.

Fig. 2(c) and (d) show the incident light angle distribution at the positions (−70 cm, 55 cm) and (0 cm, 0 cm), respectively. The angular distribution was within ±1.2° regardless of position. Fig. 2(e) shows the average incident light angle at the measurement reference plane as a function of the distance from the center of the illumination plane. The average of the angular distribution follows the arctangent characteristic of the distance from the center. This means that the solar cells at the edge are illuminated by light that is slightly tilted.

Next, we considered the effect of non-planar surface in practical curved PV modules on the roof of a car. We estimate the maximum tilt angle and height of a typical curved PV module for a car. These parameters are necessary to consider how much volume non-uniformity is acceptable for precise measurements. Although the edges of a car roof may have steeper shapes [8], we will look at the typical shape of a curved PV module. Base on the simple model shown in Fig. 1(d), we calculated the height and tilt angle of the edge. Table 1 shows the height and tilt angle of the edge for different curvature radii (1, 2, 3 m) and module size (0.5, 1, 1.5 m). For example, a module with a curvature radius of 3 m and a size of 1.5 m have a height of 9.5 cm and a tilt angle of 22.7 deg. Precise measurements require the specification of a solar simulator. Curved PV modules have a thickness of the illuminated surface relative to the incident light, so the volume uniformity of the illumination may affect the measured current–voltage curves. In addition, if the incident angle distribution is larger than the tilt angle of the curved

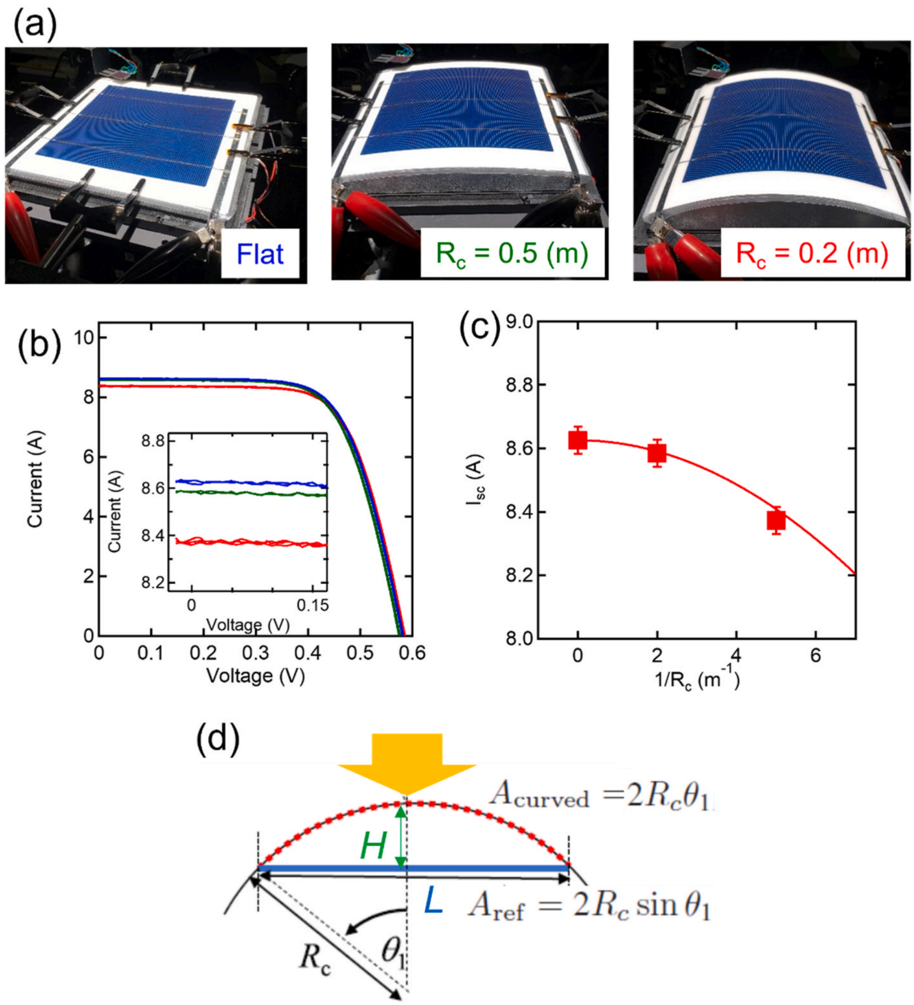

Fig. 1. (a) Schematic of the measurement of a flexible c-Si solar cell on curved stages. (b) Current–voltage curves of a flexible c-Si solar cells on curved stage with different curvatures. The inset represents the extended around short-circuit current. (c) Short-circuit current of a flexible c-Si solar cell as a function of stage curvature. (d) Schematic of a curved solar cell.

module, the curved PV module itself may be in shadow.

3.3. Measurements of curved PV modules

We measured the current–volage curves of curved PV modules with different curvature radii. Fig. 3(a) shows the curved c-Si PV modules settled at the measurement stage. The temperature of the curved PV modules was controlled by laboratory temperature, and the temperature monitored at nine points on the rear side of the module was 25.0 ± 0.2 °C during the evaluation. Fig. 3(b) shows the current-voltage curves measured under the standard test condition. The short-circuit current decreased with the curvature radius, and the maximum power of the module with R = 1000 mm is the lowest. The current–voltage curve was calculated based on the current–voltage characteristic of flat module and light distribution, and it was found that the calculated current–voltage curves almost reproduced the experimental results of the curved PV module. The calculation method follows previous research [10]. For PV module of series-connected solar cells, the curvature of the module significantly affects performance, such as short-circuit current. Considering a 6-inch c-Si solar cell, the current generated by the solar cell is about 10 A. The current generated in a solar cell is determined by the cosine effect. The more the solar cells are tilted, the smaller the photocurrent. This indicates that the amount of incident light on the maximum tilt solar cell is the limiting factor for the current in modules. Note that current mismatch resulting from curved surfaces may be mitigated in thin-film PV modules with lower shunt resistance [23]. We considered a module with 8 × 4 solar cells connected in series. The difference between the measured maximum power value and the calculated value is within 1 %.

3.4. Solar simulators for curved PV modules

Finally, we discuss the requirements for the solar simulator used to measure the current–voltage characteristics of a curved PV module. With regard to IEC standards for performance measurement protocols, power at standard test conditions and other important quantities such as temperature coefficient are specified on the label or datasheet. These quantities are measured by methods specified in international consensus standards. The challenge with curve PV modules is that there is no standard for power ratings, mainly due to the curved active layer, so that there are no specifications, labels, or data sheets.

Regarding these challenges, IEC 60904-1, which specifies the measurement of photovoltaic current–voltage characteristics, states that the active surface of the device under test shall be coplanar within ±2°, and that the reference device shall be placed on the test plane so that its active surface is coplanar within ±5° [13]. However, there is no mention of curved active surfaces tilted by more than 2°. Furthermore, the standard states that the effect of spatial non-uniformity of irradiance shall be evaluated. However, curved active surfaces with height and depth are not considered. Therefore, the current standard does not

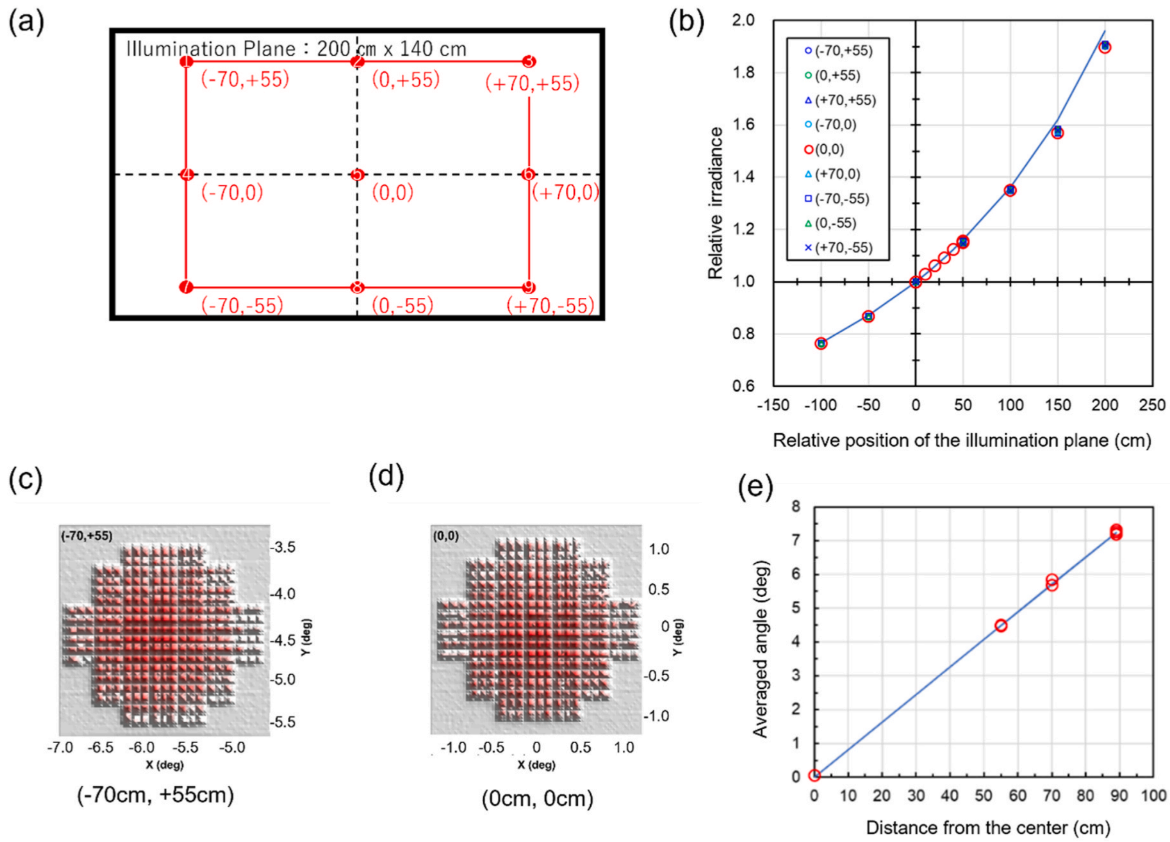

Fig. 2. (a) Schematic of the illumination plane. (b) Relative irradiance as a function of relative position in the front-to-back direction of the illumination plane. (c) Incident light angle distributions at the position (−70 cm, 55 cm) and (d) (0 cm, 0 cm). (e) Average incident light angle as a function of the distance from the center of the illumination plane.

Table 1
Height and tilt angle of the edge of curved PV modules for different curvature radii of $R = 1$, 2, and 3 m and module size of $L = 0.5$, 1, and 1.5 m.

		Height H (cm)			Tilt angle at the edge (deg.)		
		R (m)			R (m)		
		1.0	2.0	3.0	1.0	2.0	3.0
L (m)	0.5	3.2	1.6	1.0	22.7	11.3	7.5
	1.0	13.4	6.4	4.2	47.1	22.7	15.1
	1.5	33.9	14.6	9.5	76.3	34.6	22.7

specify how to measure curved active surfaces.

As discussed in the previous section, the requirements of a solar simulator are important for standardized measurements of curved PV modules. Curved PV modules have a thickness of the illuminated surface relative to the incident light, so the volume uniformity of the illumination can affect the measured current–voltage curve. Below we discuss some considerations for extending the criteria from surface non-uniformity to the volume non-uniformity. First, as stated in IEC 60904-9, the spatial non-uniformity of irradiance in a test plane is defined:

$$\text{Non-uniformity}(\%) = (\text{max.irradiance-min.irradiance})/(\text{max.irradiance} + \text{min.irradiance}) \times 100\ \% \qquad (1)$$

Next, the non-uniformity distribution in the depth is taken into account. Spatial irradiance measurements are made at several test planes at different depth. Note that the depth relative to the reference plane must be greater than the height of curved PV modules. The volume non-uniformity is evaluated from the sets of non-uniformity in different test planes using Eq. (1) and the maximum non-uniformity between the point is used. For measurements of curved PV module characteristics, where the current generation is non-uniform due to the tilted surface with respect to the normal axis, the non-uniformity of the solar simulator should be small (e.g. less than ±1.5 %) to reproduce the results of short-circuit current generation.

In addition, the curved PV module itself may be shadowed if the angle distribution of incident light is larger than the tilt angle of the curved PV module. Therefore, to avoid shadows caused by the curved PV module itself, the incident angle distribution should be smaller than the tilt angle of the curved PV modules. Collimated light is required to modules with large angles, while diffused light can be used for curved PV module with small tilt angles.

4. Conclusion

The current–voltage curves of the flexible c-Si solar cells were measured on curved stages and it was found to decrease in current with curvature. In addition, the irradiance distribution, such as spatial light intensity and incident light angle, of a solar simulator for a large PV module was characterized. It was demonstrated that the current–voltage curves of curve PV modules can be matched with the calculated current–voltage curves considering the irradiation characteristics of the solar simulator and the current–voltage curve of the flat PV modules. Solar simulators used to measure the current–voltage characteristics of a curved PV module requires the volume non-uniformity covering the volume of curved surface, and a narrow incident light angle distribution that does not cause self-shading by the curved surface.

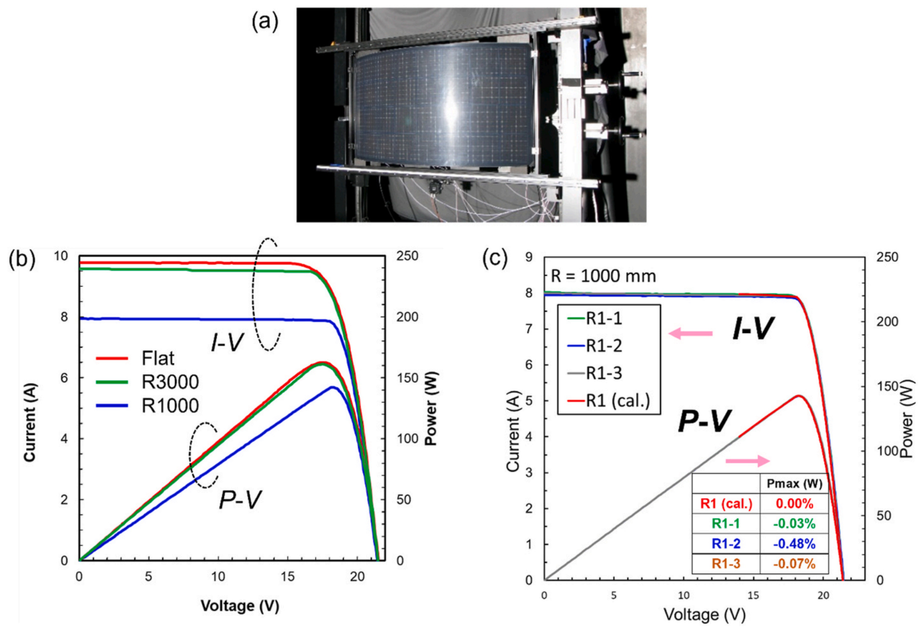

Fig. 3. (a) Photograph of curved c-Si PV modules settled for measurements. The irradiance and incident light angle distribution were measured at the in-plane positions (x, y) marked with red circles. (b) Current–voltage and power–voltage curves of the flat module and curved modules with curvatures of $R = 3000$ mm (R3000) and $R = 1000$ mm (R1000). (c) Current–voltage curves obtained for three curved modules with curvature radius of $R = 1000$ mm and that calculated from the current-voltage curves of the flat module and illumination intensity at the illumination planes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

CRediT authorship contribution statement

Takeshi Tayagaki: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Kengo Yamagoe:** Investigation, Data curation. **Munefumi Komori:** Investigation, Data curation. **Masahiro Yoshita:** Writing – review & editing, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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