Effects of gravity direction on water transport in sweetpotato plants

Ayako Tokuda and Yoshiaki Kitaya*

Environmental Sciences and Technology, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai-shi, Osaka 599-8531, Japan

Abstract

This study is a fundamental research for understanding water transport of plants under low gravity in space. To demonstrate the suppressive effect of gravity on transpiration and sap flow, we assessed transpiration rates and (T_l−T_r) as indicators of sap flow rates using the difference in the surface temperatures at 1 mm from the heated points on both sides of the petioles of sweetpotato plants under different gravity directions on Earth. Transpiration and sap flow in the plants were promoted at the inverted position. The finding in this study suggests that gravitational potential could not be ignored in water transport in plants. ©2019 Jpn. Soc. Biol. Sci. Space; doi: 10.2187/bss.33.18

Keywords; Gravity, Sap flow, Transpiration, Water potential

Introduction

As human habitation in space is gradually becoming feasible, the interest in plant culturing in space is also increasing (Monje et al., 2003; Kibe, 2017). The success of long-duration manned missions and human habitation in space will be highly dependent on stable plant culturing, because plants play several important roles on Earth as well as in controlled ecological life support systems (CELSSs) in space (Nitta, 1989). These roles include food production, CO₂/O₂ conversion, and water purification. Plant culturing in space requires sustained and scheduled crop production with rapid turnover rates.

Transpiration plays a key role in water and nutrient transportation from the root zone to the leaves. As it transports water and nutrients through the roots, stems, and petioles, it significantly sustains plant growth. Sap flow measurement enables to the direct monitoring of water transport in the stems or petioles and the indirect monitoring of the transpiration ability of the leaves. Thus, sap flow measurement can be used to evaluate plant growth. It is important to clarify the influence of microgravity on water transport in plants to facilitate the building of structures that have adequate environmental control systems for the long-duration cultivation of healthy plants in space (Monje et al., 2003). We have previously reported that wind has a considerable and positive effect on transpiration, particularly under microgravity conditions in parabolic airplane flights (Kitaya et al., 2006; Hirai and Kitaya, 2009; Tokuda et al., 2018a). Sap flow is highly correlated with transpiration (e.g., Sakuratani, 1981; Dugas, 1990; Smith and Allen, 1996). Transpiration is induced by the difference between the water potentials of the leaves and the atmosphere and drives sap flow, which refers to the water transport from the roots to the leaves. Sap flow generally depends on the “osmotic”, “pressure”, and “gravitational” potentials in plants (Holbrook, 2015a). The present study aimed to measure sap flow under a negative gravity condition on Earth and to demonstrate that the sap flow measurement method developed in a previous study (Tokuda et al., 2018c) is useful for monitoring water transport driven by transpiration in short plants. We applied (T_l−T_r), which is a sap flow index, determined based on the surface temperatures of the petioles of sweetpotato plants. In addition, we compared (T_l−T_r) in different gravity directions on Earth.

Materials and Methodes

The materials were sweetpotato plants [Ipomoea batatas (L.) Lam. cv. “Purple Sweet Road”], each approximately 10 cm in height and consisting of a leaf, a petiole, and roots. Sweetpotato is one of the candidate crops for culturing in space (Nitta, 1989; Monje et al., 2003). Vine-cuttings of the sweetpotato plant were placed in rockwool medium (36×36×40 mm; Grodan, Roermond, The Netherlands) and supplied with nutrient solution from the bottom for 14–18 days after rooting. During the experiment, the rockwool medium was supplied with sufficient air and water and was covered with a plastic sheet.

The plants were inverted after acclimation for 30 min in the reference position in which the leaf was upward and the roots were downward. Petiole surface temperatures were measured using an infrared thermography camera (VIM-384G2ULC; Vision sensing Co., Ltd., Osaka, Japan). Heat distribution on the petiole surfaces was recorded for approximately 1 hour. The thermal sensitivity was ±0.02% of the reading temperature, the minimum spatial resolution was 23×23 μm, and the emissivity value was set at 0.93 as reported by Jones (1999). White fluorescent lamps (FHP45EN; Panasonic Co., Osaka, Japan) installed on one side of the plants were used as light sources (Fig. 1a). The photosynthetic photon flux density (PPFD) received by the leaves was maintained at approximately 400 μmol m⁻² s⁻¹, air temperature was 22–24°C, the vapor pressure deficit (VPD) was 1.9–2.2 kPa, and the air velocity around the plants was 0.5 m s⁻¹.

The sap flow measurement method in the present study was according to that reported by Tokuda et al.
A tiny heater made of a nickel–chrome alloy wire (diameter, 0.2 mm) was inserted into the center of the petioles (diameters, 1.8–2.9 mm) and attached to a DC-stabilized power supply (CPS-3025L; CUSTOM Co. Ltd., Tokyo, Japan) to provide a continuous supply of electricity at 0.6–1.0 V and 0.20–0.25 A. Based on the heat condition and sap flow, heat from the heater was transferred vertically to both the leaf side (the upper side in the reference position and the lower side in the inverted position) and the root side (the lower side in the reference position and the upper side in the inverted position). Heat transfer to the leaf side increased with an increase in sap flow rate, and the difference between the surface temperatures of the leaf side ($T_l$) and that of the root side ($T_r$) increased. We assessed ($T_l−T_r$) as an indicator of sap flow rate based on the differences in surface temperatures at 1 mm above and below the heater. In addition, we determined the variation in relative surface temperature ($\Delta T$) distribution of the petiole surface temperature in the inverted position by subtracting the petiole surface temperature in the reference position. The index of sap flow (ISF) was then calculated as the difference in the $\Delta T$ values between 2 points ($T_l$ and $T_r$) based on the method described by Tokuda et al. (2018c) (Fig. 2a).

To measure water loss rate, which was essentially
the transpiration rate, mass loss in the plant system and the medium was monitored for 40 minutes each in the reference and the inverted positions using an electronic balance (HR-202; A&D Co. Ltd., Tokyo, Japan) (Fig. 1b). Triplicate measurements were obtained in different plants. Each plant consisted of two leaves, a stem, and roots in rockwool medium. The transpiration rates based on the water loss per leaf area were calculated using slopes of the linear approximation of the water loss change over time from 0 to 40 minutes after the treatment. The PPFD received by the leaf was maintained at approximately 100 μmol m⁻² s⁻¹ in the both position with the sideward lighting, the air temperature was 26.5–28.5°C, the VPD was 1.5–2.2 kPa, and the air velocity around the plants was 0.1 m s⁻¹.

Results and discussions

In the inverted position, (T_l−T_r) and the ISFs increased with time after the start of the upside-down treatment for each plant (Fig. 2). At 30 min after treatment, (T_l−T_r) was significantly greater in the inverted position than in the reference position (P<0.05, Fig. 2). When the plants were in the inverted position, the gravitational potential was confirmed as the driving force for water transport from the roots to the leaf.

Water loss in the plants was greater in the inverted position than in the reference position (Fig. 3), indicating a similar trend for water transport from the roots to the leaf. The transpiration rates based on the water loss per leaf area were found to be 42.0±7.0 mg m⁻² s⁻¹ and 34.1±7.7 mg m⁻² s⁻¹ in the inverted and reference positions, respectively, and there was a significant difference (P<0.05) between them by the paired t-test. Although gravitational potential, which is 0.01 MPa m⁻¹, suppresses upward water transport, the potential level of 0.001 MPa in plants approximately 10 cm in height in this study only has a minor effect on sap flow compared to the effect of the water potential gradient between the leaves and the atmosphere, which is −93.6 MPa at 1.1 kPa of the VPD (50% relative humidity at 20°C) (e.g., Holbrook, 2015b). Therefore, gravitational potential under unsaturated water vapor conditions is usually negligible and can be ignored, particularly in short plants.

Monje et al. (2005) reported no difference with respect to gas exchange rates between ground and microgravity conditions. However, no study has yet precisely investigated water vapor exchange between plants and the atmosphere under long-duration microgravity conditions. Gravitational potential influences water transport in plants in short time (20 seconds) microgravity conditions during parabolic airplane flights (Tokuda et al., 2018a; 2018b). Pressure gradient, which is needed for movement of water to the top of a plant through the xylem as pressure-driven bulk flow, has to be higher than the sum of frictional resistance to water movement through the stem and difference of the gravity potential between the top of the plant and the roots according to Holbrook (2015b). In this short time experiment, it was assumed that the frictional resistance did not change in the inverted plants. Therefore, a long time experiment, investigating the effect of the resistance under low gravity in the future is required.

In addition, the gravitational potential is relatively considerable and cannot be ignored as the water potential gradient between the leaves and the atmosphere is small in the generally saturated conditions that are usually observed in a closed plant culture facility with a high plant density.

The finding in this study suggests that gravitational potential could not be ignored in water transport in plants. Due to the change of gravitational water potential, the caution should be exercised in inverted plants and/or in plants under low gravity conditions such as those on the Moon (1/6 of the Earth’s gravity), Mars (1/3 of the Earth's gravity), or the International Space Station (nearly zero gravity) for a long duration. To culture healthy plants over long durations and for several life cycles, it is necessary to investigate the effect of low gravity on water transport in plants. The effect of gravity on water transport will be sustained in space.

Acknowledgments

This study was supported by the Japan Society for Promotion of Science (JSPS Grants-in-Aid for Scientific Research, 16H01646 and 18H04984) and Japan Aerospace Exploration Agency (JAXA). We also thank Dr. Liya Xiao in Osaka Prefecture University for her technical help.

Reference

Dugas, W. A. (1990) Comparative measurement of stem flow and transpiration in cotton. Theor. Appl. Climatol.,
Jones, H. G. (1999) Use of thermography for quantitative studies of spatial and temporal variation of stomatal conductance over leaf surfaces. Plant, Cell and Environ., 22, 1043–1055.

Hirai, H., Kitaya, Y. (2009) Effects of gravity on transpiration of plant leaves. Ann. N. Y. Acad. Sci., 1161, 166–172.

Holbrook N. M. (2015a) Water and Plant Cells. In: Taiz, L., Zeiger, E., Møller, I. and Murphy, A. (eds) Plant Physiology and Development. Sinauer Associates, Inc., Oxford, pp 83–98.

Holbrook N. M. (2015b) Water Balance of Plants. In: Taiz, L., Zeiger, E., Møller, I. and Murphy, A. (eds) Plant Physiology and Development. Sinauer Associates, Inc., Oxford, pp 99–118.

Kibe, S. (2017). Introduction of the Society of Eco-Engineering. Int. J. Microgravity Sci. Appl., 34, 340204.

Kitaya, Y., Kawai, M., Takahashi, H., Tani, A., Goto, E., Saito, T., Shibuya, T., Kiyota, M. (2006) Heat and gas exchanges between plants and atmosphere under microgravity conditions. Ann. N. Y. Acad. Sci., 1077, 244–255.

Monje, O., Stutte, G., Goins, G., Porterfield, D., and Bingham, G. (2003). Farming in space: environmental and biophysical concerns. Advances in Space Research, 31, 151–167.

Monje, O., Stutte, G., Chapman, D. (2005) Microgravity does not alter plant stand gas exchange of wheat at moderate light levels and saturating CO₂ concentration. Planta, 222, 336–345.

Nitta, K. (1989). System configuration problems for material balancing in CELSS. CELSS Journal, 1, 5–12.

Sakuratani, T. (1981) A heat balance method for measuring water flux in the stem of intact plants. J. Agric. Methanol., 37, 9–17.

Smith, D. M., Allen, S. J. (1996) Measurement of sap flow in plant stems. J. Exp. Bot., 47, 1833–1844.

Tokuda, A., Kitaya, Y., Hirai, H., Yano, S. (2018a) Promoting stem sap flow of sweetpotatoes under low gravity with forced air movements. Trans. Japan Soc. Aeronaut. Sp. Sci. Aerosp. Technol. Japan, 16, 53–56.

Tokuda, A., Kitaya, Y., Hirai, H., Hashimoto, H., Inatomi, Y. (2018b) Effects of gravity on stem sap flow and water and heat exchange in the leaves of sweetpotato. Int. J. Microgravity Sci. Appl., 35, 350302.

Tokuda, A., Kitaya, Y., Hirai, H. (2018c) Development of a simple thermal method for measuring sap flow in plants for space experiments. Biol. Sci. Space, 32, 17–21.