Spatiotemporal monitoring of intracellular metabolic dynamics by resonance Raman microscopy with isotope labeling†

Yusuke Yonamine, Kotaro Hiramatsu, Takuro Ideguchi, Tomomi Fujiwara, Yoshiko Miura, Keisuke Goda and Yu Hoshino

Cellular metabolites are valuable in a diverse range of applications. For example, the unicellular green alga Haematococcus lacustris produces as a secondary metabolite the carotenoid pigment astaxanthin (AXT), which is widely used in nutraceutical, cosmetic, and food industries due to its strong antioxidant activity. In order to enhance the productivity of H. lacustris, spatial and temporal understanding of its metabolic dynamics is essential. Here we show spatiotemporal monitoring of AXT production in H. lacustris cells by resonance Raman microscopy combined with stable isotope labeling. Specifically, we incorporated carbon dioxide (13CO2) labeled with a stable isotope (13C) into H. lacustris cells through carbon fixation and traced its conversion to 13C-AXT using our resonance Raman microscope. We incubated H. lacustris cells under various conditions by switching, pulsing, and replacing 13CO2 and 12CO2. By measurement of these cells we determined the fixation time of 13C-carbon, visualized the intracellular localization of 13C- and 12C-AXTs, and revealed the dynamic consumption–production equilibrium of the accumulated AXT. This work is a valuable step in the development of effective screening criteria for high AXT-producing H. lacustris cells.

Introduction

The observation and analysis of intracellular dynamics is essential to the study of cell biology. For example, organelles undergo dynamic morphological changes during autophagy or cell death by apoptosis or necrosis. Microtubules and nucleolus form a wide range of spatial configurations in cell-cycle transitions including cell division, differentiation, and morphogenesis. Mitochondria mount metabolic defenses against intracellular pathogens in response to infection. Beyond basic science, cellular metabolites produced by animal cells and microbes are widely used in the pharmaceutical, nutraceutical, cosmetic, and food industries, and increasing metabolism production efficiency by cell engineering remains a major goal. For instance, antibodies produced by Chinese Hamster Ovary (CHO) cells are used as therapeutic agents, and secondary metabolites produced by microalgae cells are used as biofuels and nutritional supplements. Metabolic fluxes in a living cell are highly regulated and varied in response to environmental changes, bioactive substances, and transitions of the cell cycle. Accordingly, the spatiotemporal observation of intracellular metabolic dynamics, including production, accumulation, and transportation, is foundational to the understanding of cellular metabolism. It is also effective for developing screening criteria for applications such as those above as well as for regenerative medicine and cell therapy.

Fluorescence microscopy, with the help of fluorescent probes, is widely used to identify the intracellular localization and distribution of metabolites with subcellular resolution. However, such fluorescent labeling inevitably comes with several fundamental drawbacks when observing intracellular metabolic dynamics. First, the hydrophobicity of small-molecule fluorescent probes and the bulkiness of fluorescent protein labels often disturb natural biological functions and
lead to cellular toxicity. Second, intracellular fluorescent staining with fluorescent dyes suffers from non-specific binding and misdistribution, leading to potential errors in quantitative live imaging. Third, sequential labelling such as pulse-chase analysis using protein tags is not applicable to the study of small metabolites. For these reasons, fluorescence microscopy is not always suitable for monitoring intracellular metabolic dynamics.

On the other hand, Raman microscopy together with stable isotope (SI) labeling provides significant advantages in monitoring intracellular metabolic dynamics. First, since SI probes can be incorporated and metabolized in cells similarly to the original substrates, their use does not lead to cellular toxicity, interference with biological functions, or non-specific binding. Second, the metabolic process from incorporation to production can be tracked by exposing cells to an SI-labeled substrate and detecting SI-labeled products. Third, by analysis of the peaks of Raman spectra, Raman mapping quantifies the ratio of SI-labeled products to unlabeled products at spatial positions of interest. Though Raman microscopy with SI-labeled substrates has revealed the cellular anabolic processes of biopolymers including proteins, DNAs, and lipid droplets, the spatiotemporal dynamics of secondary metabolites has not been monitored to date despite the usefulness of these metabolites in a wide range of applications.

In this paper, we show spatiotemporal monitoring of intracellular metabolic dynamics, for screening the production of secondary metabolites, using resonance Raman microscopy with an SI-labeled substrate exposed to various conditions (Fig. 1). Specifically, we investigated the biosynthesis process of a commercially valuable carotenoid, astaxanthin (AXT), produced by the unicellular photosynthetic alga Haematococcus lacustris, a species known to accumulate AXT under induced carotenogenesis. We incorporated carbon dioxide (13CO2) labeled by an SI (13C) into H. lacustris cells accumulating 13C- or 12C-AXT. (a) Resonance Raman spectroscopy of mixed H. lacustris cells that accumulate 13C- or 12C-AXT by resonance Raman imaging with 12CO2 and 13CO2 incubation. By measurement of these cells we determined the fixation time of 13C-carbon, visualized the intracellular localization of 13C- and 12C-AXTs, and revealed the dynamic consumption–production equilibrium of the accumulated AXT. We believe this work represents a valuable step in the development of effective screening criteria for high AXT-producing H. lacustris cells.

Results and discussion

Resonance Raman imaging of H. lacustris cells accumulating 13C-AXT

First, we performed resonance Raman imaging of H. lacustris cells incubated with 13CO2, long enough for 13CO2 to convert to 13C-AXT. We induced intracellular production of AXT for 5 days under nitrogen deficiency and strong light irradiation and measured the resonance Raman spectra of the cells. We obtained typical resonance Raman spectra of carotenoids including v1–v4 peaks from the resultant red cyst cells (Fig. 2a, red). The v1–v4 peaks are assigned to vibrational modes as follows: v1, C=C stretching; v2, C–C stretching/C–H in-plane bending; v3, CH3 rocking; v4, C–H out-of-plane wagging. Spectra consist mainly of peaks corresponding to AXT, as it is the major ingredient (>90%) of carotenoid production by H. lacustris. The AXT spectra of cells incubated with 12CO2 are shifted to lower wavenumbers compared to those of cells incubated with 13CO2 (Fig. 2a). This red shift is attributed to the substitution of 13C by the heavier isotope 12C, resulting in a lower frequency of molecular vibration. In particular, large shifts were observed in v1 and v2 peaks, which are assigned to vibrational modes of carbon–carbon bonds. The largest shift (32 cm−1) was observed in the v1 peak, which shifted from 1518 cm−1 (12C: green) to 1486 cm−1 (13C: red). These results indicate that 13CO2 was incorporated into H. lacustris cells through carbon fixation and that 13C-carbon was converted to AXT through the non-mevalonate pathway and subsequent carotenogenesis.

We then demonstrated discrimination of H. lacustris cells accumulating 13C- or 12C-AXT by resonance Raman imaging with 12CO2 and 13CO2 incubation. We visualized the spatiotemporal dynamics of secondary metabolites in single red (13C) and green (12C) AXT-producing H. lacustris cells.
based on the spectral shift. We mixed in equal number *H. lacustris* cells that accumulated $^{13}$C- and those that accumulated $^{12}$C-AXT, and then analyzed the cell mixture by Raman mapping. Raman images were generated by classical least squares modeling of the $^{13}$C- and $^{12}$C-AXT spectra obtained during the long-term induction. At each image pixel position, a linear combination of factors was calculated to estimate the measured spectrum. $^{13}$C- and $^{12}$C-AXT in the images were color-coded as red and green, respectively. As a result, the two types of cells were clearly discriminated (Fig. 2c). This result shows the advantage of Raman imaging over bright field microscopy (Fig. 2b) for detecting targets labeled with stable isotopes.

**Resonance Raman spectroscopy of *H. lacustris* cells incubated with a mixture of $^{13}$CO$_2$ and $^{12}$CO$_2$**

Second, we investigated the resonance Raman spectral shift of AXT in *H. lacustris* cells incubated with $^{13}$CO$_2$ and $^{12}$CO$_2$ mixed in various ratios. We induced production of AXT in the cells under various $^{13}$CO$_2$ ratios ($^{13}$CO$_2$: 0, 25, 50, 75, and 100 vol%) for 24 h (Fig. 3a). The Raman peaks of AXT ($v_1$ and $v_2$) gradually shifted toward lower wavenumber positions as the $^{13}$CO$_2$ ratio increased (Fig. 3b). When plotting the ratio of $^{13}$CO$_2$ versus the wavenumber of each peak ($v_1$, $v_2$, and $v_3$), all showed a linear relationship (Fig. 3c). The slope ($m$) of the $v_1$ peak, attributed to C=C stretching, has a larger absolute value ($v_1$: $m = -0.33$) than that of the $v_2$ peaks, which include a contribution from C=C stretching ($v_2$: $m = -0.25$, $v_3$: $m = -0.22$). These results are congruent with observed resonance Raman spectral shifts of carotenoids (mainly β-carotene) in cyanobacterial cells incubated with a $^{13}$C source. *H. lacustris* cells fix $^{13}$CO$_2$ and $^{12}$CO$_2$ gases with equal probability, since stable isotopes have the same biochemical properties. Consequently, the carbon ratio of $^{13}$C and $^{12}$C in an AXT molecule produced in a cell is presumably the same as the ratio of $^{13}$CO$_2$ and $^{12}$CO$_2$ in the culturing atmosphere. On the other hand, the ratio of the $^{13}$C carbon–carbon bond wavenumber ($\sigma_{13C}$) to the $^{12}$C carbon–carbon bond wavenumber ($\sigma_{12C}$) corresponds to the square root of the ratio of the reduced masses, given that the wavenumber is defined as: $\sigma = k/2\pi\sqrt{m/\mu}$, where $k$ is the spring constant of the corresponding chemical bond and $\mu$ is the reduced mass. In fact, all of the ratios of resonance Raman peaks ($\sigma_{13C}/\sigma_{12C}$) are constant ($v_1$: 0.979; $v_2$: 0.983; $v_3$: 0.978; Fig. 3b and c) and approximately consistent with the theoretical value ($\sigma_{13C}/\sigma_{12C} = 0.960$). These results show that the resonance Raman spectra of AXT in *H. lacustris* cells incubated with a mixture of $^{13}$CO$_2$ and $^{12}$CO$_2$ shift to lower wavenumbers in a linear manner corresponding to the $^{13}$CO$_2$ ratio in the culturing atmosphere.

**Resonance Raman imaging of *H. lacustris* cells incubated with atmosphere switching from $^{13}$CO$_2$ to $^{12}$CO$_2$**

Third, we switched the incubation atmosphere from $^{13}$CO$_2$ to $^{12}$CO$_2$ during AXT induction, and then investigated the ratios of $^{13}$C- and $^{12}$C-AXT in *H. lacustris* cells by resonance Raman imaging. We varied the time to switch from $^{13}$CO$_2$ to $^{12}$CO$_2$ during the 24 h incubation period to investigate cells incubated with $^{13}$CO$_2$ for 12 h, 15 h, 18 h, 21 h, and 24 h (Fig. 4a). In most cases, resonance Raman spectra of the *H. lacustris* cells were a superposition of the $^{13}$C-AXT spectrum (peaks: $v_2$: 1128 cm$^{-1}$ and 1173 cm$^{-1}$; $v_1$: 1484 cm$^{-1}$; in red) and the $^{12}$C-AXT spectrum (peaks: $v_2$: 1156 cm$^{-1}$ and 1192 cm$^{-1}$; $v_1$: 1514 cm$^{-1}$; in green) with varying intensities of the two spectra (representative four spectra are shown in Fig. 4b). This is in contrast to the gradual red shift observed in spectra of cells incubated with a mixture of $^{13}$CO$_2$ and $^{12}$CO$_2$ (Fig. 3). The results of this atmosphere switching experiment indicate that cells contain both 100% $^{13}$C-AXT and 100% $^{12}$C-AXT in various proportions, with no or a negligible amount of AXT molecules composed of both $^{13}$C- and $^{12}$C-carbons. This can be attributed to the rapid conversion rate from carbon source to AXT molecule, due to the small molecular size of AXT. In other words, after switching from $^{13}$CO$_2$ to $^{12}$CO$_2$, the $^{13}$C-carbon source was consumed rapidly for AXT production, and then the carbon source quickly switched to $^{12}$C-carbon, resulting in productions of 100% $^{13}$C-AXT and 100% $^{12}$C-AXT. In resonance Raman images generated by the classical least squares modeling of the $^{13}$C- and $^{12}$C-AXT spectra, *H. lacustris* cells are represented as a gradation of red ($^{13}$C-AXT) and green ($^{12}$C-AXT) in an RGB color model (e.g., Cell 1, yellow-green; Cell 2, yellow; Cell 3, orange; Cell 4, red-orange; Fig. 4b), since they include both 100% $^{13}$C-AXT and 100% $^{12}$C-AXT. On the other hand, AXT inside of a cell was distributed non-uniformly, suggesting that the AXT-accumulation process was still in a transition period to maturation after AXT-induction at 24 h (Fig. 4b). Notably, localization of $^{13}$C-AXT (red) and $^{12}$C-AXT (green) was observed inside some cells (Fig. S1†), revealing the progression of carbon fixation and conversion to AXT.
We then observed the *H. lacustris* cells with low-magnification resonance Raman images and investigated the comprehensive changes of $^{13}$C-AXT in the cells (Fig. 4c). As the incubation time with $^{13}$CO$_2$ increased, green color ($^{13}$C-AXT) decreased and red color ($^{12}$C-AXT) increased, as observed in resonance Raman images of cells incubated with $^{13}$CO$_2$ for 12 h, 15 h, 18 h, and 21 h (Fig. 4c). This gradual change in color indicates that *H. lacustris* cells have CO$_2$ fixation activity during the 12 h to 21 h period and then complete the conversion to AXT by the end of the incubation (24 h). On the other hand, comparing the images at 21 h and 24 h, no significant color change is observed, showing only red color ($^{12}$C-AXT) without green color ($^{13}$C-AXT). This result indicates that the conversion process from $^{12}$CO$_2$ fixation to $^{12}$C-AXT production was incomplete during this period (21–24 h). In order to quantitatively support this, we measured resonance Raman spectra of 30 cells (at the center of the cells) randomly selected from individual images and calculated the $^{13}$C-AXT ratios by spectral separation using a multivariate curve resolution–alternating least squares (MCR-ALS) algorithm (Fig. 4d). From these spectra, we confirmed that $^{13}$C-AXT accumulated until 21 h and became saturated afterwards. We then investigated the activity of CO$_2$ fixation and AXT production after 24 h. After 24 h of $^{13}$CO$_2$, the incubation atmosphere was switched from $^{13}$CO$_2$ to $^{12}$CO$_2$ at 6 hour intervals, and the total AXT-induction time was 48 h (Fig. S2a†). In these cases, accumulation rate of $^{13}$C-AXT decreased (Fig. S2b and c†), which indicates that the conversion activity from 24 h to 48 h was lower than that of the 12 h to...
24 h period. As demonstrated above, the active conversion period from CO₂ fixation to AXT production can be probed by switching from ¹³CO₂ to ¹²CO₂ at various times and comparing the difference of ¹³C- or ¹²C-AXT accumulation by resonance Raman imaging.

Resonance Raman imaging of ¹³C-AXT in H. lacustris cells labeled by pulse incubation with ¹⁴CO₂

Fourth, we labeled AXT in H. lacustris cells by pulse incubation, where the duration of incubation with ¹³CO₂ was shorter, and detected ¹³C-AXT by resonance Raman imaging to specify the carbon fixation time. In the aforementioned incubations with the switching of ¹³CO₂ to ¹²CO₂, whether ¹³CO₂ was fixed at earlier or later times could not be determined, since the ¹³C-AXT indicated by the red color accumulated during the ¹³CO₂ incubation. In this experiment, we incubated the cells with ¹³CO₂ for a constant “pulse” of time (9 h), with the remaining incubation under ¹²CO₂ (15 h), for a total AXT induction time of 24 h. The ¹³CO₂ pulse incubations were shifted by 3 h in the timeline (Fig. 5a) to probe the carbon fixation time. We calculated the ¹³C-AXT ratios of 30 cells randomly selected for each ¹³CO₂ pulse timing (Fig. 5b). The plot shows that ¹³CO₂ fixation and the resultant ¹³C-AXT production are significantly higher in the late ¹³C-induction phases (iv) 9–18 h, (v) 12–21 h, (vi) 15–24 h), while both are lower in the early ¹³C-induction phases (i) 0–9 h, (ii) 3–12 h, (iii) 6–15 h). Notably, there is a large gap between conditions (iii) and (iv), indicating that CO₂ is actively fixed and converted into AXT after 15 h. Among the late pulse incubations, conditions (v) and (vi) show higher ¹³C-AXT ratios than condition (iv) (t-test; p < 0.05), whereas no significant difference was observed (t-test; p = 0.20) between (v) and (vi). These results indicate that the activity of carbon-fixation and conversion is high during the 15 to 21 h period of incubation.

We then compared the ¹³C-AXT ratios of H. lacustris cells in the same resonance Raman image frame. We represent only ¹³C-AXT in pseudo color (Fig. 5c) to highlight ¹³C-carbon fixed during the pulse incubation, rather than representing both ¹³C-AXT (red) and ¹²C-AXT (green) in the RGB color model (Fig. S3a†). Cells that actively fixed ¹³CO₂ and converted it to ¹³C-AXT are clearly detected in the image of condition (v) 12–21 h, while such cells were scarcely observed in the image of condition (i) 0–9 h or the image of the control condition, which was incubation under only ¹²CO₂. These results demonstrate that this method of pulse incubation can be useful for screening active H. lacustris cells which show a high efficiency of carbon-fixation and AXT-conversion.

Resonance Raman imaging of replacing ¹³C-AXT by ¹²C-AXT by incubating with ¹²CO₂

Lastly, we accumulated ¹³C-AXT in H. lacustris cells and then replaced it with ¹²C-AXT by incubating the cells under ¹²CO₂.

Fig. 5 Resonance Raman imaging of ¹³C-AXT in H. lacustris cells labeled by pulse incubation with ¹³CO₂. (a) Incubation timeline of H. lacustris cells with ¹³CO₂ incubation pulsed (9 h) at various timings in 24 h. (b) Box-and-whisker plot of ¹³C-AXT ratios in the resonance Raman spectra of H. lacustris cells (n = 30). ¹²C shows a control culture with ¹²CO₂ incubation. (c) Low-magnification resonance Raman images of H. lacustris cells. The ratio of ¹³C-AXT is represented in pseudo-color. Scale bars: 100 μm.

Fig. 6 Resonance Raman imaging of replacing ¹³C-AXT by ¹²C-AXT in H. lacustris cells by incubating with ¹²CO₂. (a) Incubation timeline of H. lacustris cells with ¹²CO₂ incubation following 24 hours of ¹³CO₂ incubation. (b) Box-and-whisker plot of ¹³C-AXT ratios in the resonance Raman spectra of H. lacustris cells (n = 30). (c) Low-magnification resonance Raman images of H. lacustris cells. ¹³C- and ¹²C-AXT are color-coded in red (¹³C) and green (¹²C), respectively. Scale bars: 100 μm. Color bars: intensities of Raman spectra of ¹³C- (red) and ¹²C-AXT (green).
We induced 13C-AXT production in H. lacustris cells for 24 h by incubation under 13CO2 and then replaced the atmosphere with 12CO2 for different durations (3 h increments) before observation (Fig. 6a). Calculation of the 13C-AXT ratios of 30 cells randomly selected for each condition showed a large dispersion of 13C-AXT ratios, which reflects the difference in 12C-AXT production activity among the cells (Fig. 6b). Interestingly, we observed that 13C-AXT in some cells was completely replaced with 12C-AXT after 12 h (Fig. 6b and c), suggesting that AXT is in dynamic equilibrium between consumption and production. This information on carbon flow cannot be obtained by merely detecting non-labeled AXT and thus demonstrates the advantage of combining resonance Raman imaging with 13C-labeling. Furthermore, we observed heterogeneity of 13C-AXT (red) and 12C-AXT (green) in a single cell after incubation with 12CO2, but the AXTs became homogenized as the time of incubation with 12CO2 was extended (Fig. 7). Specifically, 12C-AXT infiltrated from the edge of the cell towards its center (Fig. 7a). In fact, the resonance Raman spectra around the cell periphery confirmed that the ratio of 12C-AXT was high at the edge and low at the center (Fig. 7b). This observation can be attributed to the transportation of newly produced 12C-AXT precursors to lipid droplets around the center.55,56 In an intermediate cell during encystment, chloroplasts, which produce an AXT precursor, are located around the cell periphery, while oil droplets, which serve as a “sink” for AXT, are located around the nucleus at the center.55,56 The newly produced 100% 12C-AXT precursors are delivered to the oil droplets from the periphery, converted to 13C-AXT by an enzyme inside, and mixed with pre-existing 100% 13C-AXT. Consequently, a gradient of 12C-AXT and 13C-AXT forms, causing heterogeneity in a single cell. These results demonstrate that the distribution of AXTs produced at different times can be visualized in a single cell by resonance Raman imaging combined with 13C- and 12C-labeling.

Conclusions

In this paper, we demonstrated spatiotemporal monitoring of AXT production in H. lacustris cells, incubated under varying 13CO2 and 12CO2 atmospheric conditions, by resonance Raman imaging. First, we induced AXT production in H. lacustris by incubating the cells with 13CO2 for enough time to produce 13C-AXT, the resonance Raman spectrum of which shows red shifts compared to that of 12C-AXT. This result shows that 13CO2 was incorporated into H. lacustris cells through carbon fixation and that 13C-carbon was converted to AXT through cellular metabolism. Based on the spectral difference between 12C- and 13C-AXT, we clearly discriminated H. lacustris cells accumulating 13C- or 12C-AXT by resonance Raman imaging. Second, we investigated the resonance Raman spectral shift of AXT in H. lacustris cells when incubated with a mixture of 12CO2 and 13CO2 gases in various ratios. We observed that the resonance Raman spectra shifted to positions at lower wavenumbers in a linear manner corresponding to the 12CO2 ratio of the culturing atmosphere. Third, we switched the incubation atmosphere from 13CO2 to 12CO2 at various times and then investigated the ratios of 13C- and 12C-AXT in the cells by resonance Raman imaging. The results indicated that the cells
contained both $^{13}$C-AXT and $^{12}$C-AXT in various proportions. By comparing via resonance Raman imaging the differences in $^{13}$C- and $^{12}$C-AXT accumulation, the active conversion period from CO$_2$ fixation to AXT production could be probed. Fourth, we labeled AXT with $^{13}$C by incubating cells under $^{13}$CO$_2$ for short pulses of time, to specify the active time of carbon fixation and conversion. Lastly, we accumulated $^{13}$C-AXT in H. lacustris cells in advance and subsequently replaced it with $^{12}$C-AXT by incubating the cells under $^{12}$CO$_2$ for different durations. We observed a high variation between cells in the rate at which $^{13}$C-AXT decreased, reflecting individual differences in $^{12}$C-AXT production activity among cells. In some cells, $^{13}$C-AXT was completely replaced with $^{12}$C-AXT, suggesting that AXT is in dynamic equilibrium between consumption and production. Furthermore, localizations of $^{13}$C-AXT and $^{12}$C-AXT in a single cell were observed by magnified resonance Raman imaging.

Our method provides spatiotemporal information for single cells, including the conversion process from substrate to metabolite, the distribution process of the metabolite, and the turnover of the metabolite in dynamic equilibrium. By virtue of non-cytotoxic labelling and non-invasive imaging, long-term monitoring of metabolic dynamics in living cells can be achieved. Furthermore, by integrating our method with technologies for single cell isolation, the intracellular metabolism of an identified cell can be monitored. When combined with state-of-the-art Raman spectroscopy techniques that have higher spatiotemporal resolution, such as stimulated Raman scattering (SRS)\textsuperscript{55–66} or coherent anti-Stokes Raman scattering (CARS),\textsuperscript{61–63} the process of metabolite distribution can be monitored in a single cell with further detail. Leveraging such information for biotechnological production of target metabolites could provide significant value in terms of productivity. Furthermore, using Raman-activated cell sorting (RACS)\textsuperscript{64–66} will enable screening for cells with high metabolite productivity from a genetically diverse cell population.

Conflicts of interest

There are no conflicts to declare.

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